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SPECIAL MEETING, MARCH 12TH, 1889.

SUBJECT:

The Efficiency of Methods of Artificial Illumination.

BY EDWARD L. NICHOLS.

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AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

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The thirty-third meeting of the Institute was held on March 12th, at the College of the City of New York. Vice-President T. C. Martin called the meeting to order at 8 o'clock and said:

In the absence of our Secretary, Mr. Ralph W. Pope, who is unfortunately detained by sickness in his family, it devolves upon me to introduce the business of the evening, and as I happen also to be one of the officers, it also becomes my duty to elect myself to the chair. I have much pleasure in announcing as the subject of the evening, "The Efficiency of Methods of Artificial Illumination," the paper upon which will be read by our well-known fellow member, Prof. E. L. Nichols of Cornell University, and I have much pleasure in calling upon the Professor to read his paper.

Prof. Nichols read the following:

THE EFFICIENCY OF METHODS OF ARTIFICIAL ILLUMINATION.

BY EDWARD L. NICHOLS.

Of human industries of the present day none perhaps, save those which have to do with providing the race with food, clothing, shelter and fuel, is more important to the cause of material welfare than that which deals with the production of artificial light, and he who seeks a means of measuring the material civilization reached by a nation might find an excellent criterion in the progress which it exhibits in the art of illumination.

The problem of comparing the various methods of artificial lighting which are in vogue at the present day is one of great interest, whether we view it from the commercial standpoint, taking the cost of production as our controlling factor, or from the broader basis of relative usefulness, cost being relegated to a secondary position, or, finally, from the purely scientific point of view. From whichever side we approach this question, we are led inevitably to the consideration of certain elements which are alike of scientific, utilitarian and commercial importance.

At first sight the attempt to determine the relative value of two sources of light would seem to be a simple matter. The number of factors, however, which enter into such a determination is surprisingly large, and many of them are of a character which makes it difficult to give them definite and complete expression. Of these the greater part are, indeed, commonly left out of account altogether, for the sake of simplicity, and we content ourselves with an antiquated and totally insufficient measure of our sources of illumination, which we call candle-power. It is to these other elements which enter into the question of the character of artificial light—such, for instance, as have to do with its *quality*—but which are, as a rule, quite lost sight of, to which I would ask your attention this evening, together with a discussion of those which are commonly made use of in photometry. If, in so doing, I am led to speak of methods which belong to the realm of pure science,

I trust that you will agree with me in thinking that the results are not unimportant even to those whose interest in the problem of the production of artificial light is purely utilitarian.

In the important question of the efficiency of a light-producing machine or process, the practice of to-day is very far from having reached that degree of exactness of expression which we demand in other cases of the transformation of energy. In electric lighting the energy expended is readily determined in absolute measure, or in that excellent practical unit, the *Watt*. In lieu of any attempt to express the useful energy obtained, however, we still content ourselves in practice with that most unscientific unit, the candle-power, based upon a source of illumination which is particularly subject to fluctuations of intensity and color. Even as used in the Bunsen photometer the shortcomings of the standard candle are sufficiently apparent; but no one who has not attempted to study it by methods which make it possible to detect changes of color as well as of brightness, can fully appreciate its fickleness.

Such as it is, we do not, moreover, make the best of the standard candle as a basis of comparison of artificial lights. We speak of a 16-candle incandescent lamp, for instance, meaning oftentimes "mean spherical candle-power" and then we compare it with a petroleum or gas flame, measured in the horizontal plane only, much to the disadvantage of the electric lamp. The study of the distribution of intensities in accordance with the very complete system devised for that purpose by the Franklin Institute Committee in 1884, affords an invaluable means of comparing the performance of various types of incandescent lamps; but the adoption of "mean spherical candle-power" as obtained by that method, is, to say the least, misleading when it comes to the comparison of electric lamps with candles, oil or gas. It is to be hoped that when the present confusion of methods of measuring candle-power now existing in the electric lighting establishments in this country is supplanted by a recognized system, the fairer standard already established by law in England, viz., mean horizontal candle-power, may be adopted. It is, however, in the comparison of arc and glow lamps that the latter are put at the greatest disadvantage. Here we pit the incandescent lamp, using mean spherical candle-power as our basis, against candle-power measured at the angle at which the arc light sends out the greater part of its rays. Indeed, in too many cases, it is not with the ac-

tual intensity even in this most favorable position with which we have to do, but with an estimated or "nominal" candle-power which the arc, in matter of fact, never approaches.

The electric arc stands quite alone, for the purposes to which it is adapted, and need fear no rivals. It does not need to be estimated upon any fictitious basis, and the continuance of the pernicious practice of ascribing to it powers of illumination which it does not possess, must, in a great measure, be charged to the account of the standard candle; for with the best intentions in the world, the comparison of sources of light differing so widely in color as the candle and the electric arc, is nothing more than a rude approximation, leading by its very inaccuracy to the temptation of the grossest exaggeration.

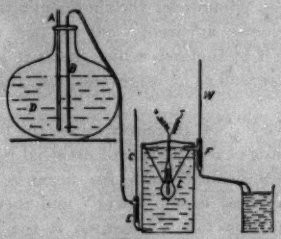

FIG. 1.

There are, fortunately, better methods of estimating the efficiency of a lamp than that which is based upon candle-power.

We may, for instance, determine the ratio of the energy of the light-giving radiation to that of the total radiation of the source of illumination. The efficiency of the incandescent lamp, according to this definition, has been recently determined by Mr. Ernest Merritt,[2] of the Physical Laboratory of Cornell University. Mr. Merritt followed two independent methods of investigation. In his first experiments the lamp was placed in a calorimeter constructed entirely of glass, Fig. 1, through which a constant flow of water was maintained. The temperature of the water upon entering and upon leaving the calorimeter was measured by means of the thermometers E and F. From this difference of temperature and the amount of water discharged in a given time, the heat absorbed by the calorimeter was calculated; proper correc-

[2] Ernest Merritt, *American Journal of Science*, vol. 37, p. 167.

tions for loss of heat by radiations, etc., being applied. Now the water with which the calorimeter was filled is nearly transparent to the light-giving radiations from the lamp, and almost entirely opaque to the longer wave lengths which constitute the so-called heat spectrum. To have assumed it to be entirely so, would, however, have involved very considerable errors, and the diathermancy of the calorimeter on the one hand and its power of absorbing the luminous wave-lengths on the other, were accordingly carefully determined by methods long since elaborated and made use of by Melloni and by his distinguished English follower, Professor Tyndall. By applying these and other necessary corrections, we are able to calculate very accurately in watts, the non-luminous radiation from the lamp. The ratio of the total radiation, obtained either by submerging the lamp in a metallic calorimeter or by direct computation from the current and electromotive force gives the actual efficiency of the lamp considered as a light-making machine. The result is not a gratifying one, when we compare this process with most others in which energy is transformed. The efficiency of the best types of incandescent lamps, previous to the introduction of the recent three-watts-per-candle lamps now in successful operation, which would doubtless make a somewhat better showing, was found to be rather under than over five per cent. at normal candle-power; the values ranging from 0.5 per cent. to 6.5 per cent. The last named value for the efficiency was attained only at a temperature incompatible with any considerable length of life. The results obtained in this investigation are shown in table i.[a] and in the accompanying diagram, Fig. 3.

In this table w is the total energy, in watts; L the energy of the light, also measured in watts; and C. P. the candle-power.

The second method pursued by Mr. Merritt was intended rather as a check upon the results already obtained than in the expectation of gaining further data. The rays of the lamp were allowed to fall upon the face of a delicate thermopile placed at a

[a] Dr. Blattner, in an Inaugural Dissertation, published at the University of Zürich, gives similar values for the efficiency of the incandescent lamp. He finds, as the result of extended measurements with the glass calorimeter, that * * * "at the normal temperature of incandescence, where the intensity lies in the neighborhood of 16 candles, the efficiency does not rise above five per cent. to six per cent."—Emil Blattner; *Der Optische Nutzeffect der Glühlampen*, Frauenfeld, 1886.

distance of about 60 cm. The thermopile was in circuit with a low resistance galvanometer of the well-known "tripod pattern"

Table I.[4]

Lamp A. Edison.

E. M. F.	W.	C.P.	L.	$\frac{L}{W}$	$\frac{L}{C.P.}$
74.2	31.6	0.9	0.18	0.005	0.59
91.6	56.2	4.8	0.98	.012	0.14
97.3	64.6	7.3	1.13	.017	0.15
100.3	69.3	8.9	1.62	.023	0.18
107.6	81.6	14.6	2.97	.036	0.20
109.3	84.4	16.3	4.57	.054	0.28
124.1	115.4	38.2	7.46	.065	0.19

of Sir William Thomson. The deflection of the galvanometer was taken as a measure of the total radiation, luminous and non-luminous, which fell upon the face of the pile. A cell containing a solution of alum was now interposed, and the reduction in the galvanometer noted. The arrangement of this apparatus is shown in Fig. 2.

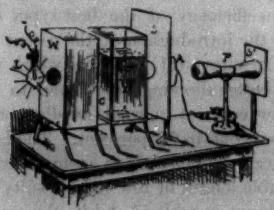

FIG. 2.

An aqueous solution of alum fulfills much more nearly the desired condition of complete opacity to "dark heat" and complete transparency to the rays of the visible spectrum than any other substance, but a certain small percentage of the longer wave lengths will pass through such a bath, and a considerably larger percentage of light-giving rays will be cut off by it. The proper corrections are, however, easily determinable, and when in this case they had been determined and applied, the ratio of total to luminous radiation was found to be in gratifying agreement with the efficiency obtained by the calorimetric method already described. See table ii.

[4] Tables I and II, and figures 1 and 2, are taken from Mr. Merritt's paper, already referred to.

TABLE II.

Lamp B.

An Edison 16 c. p. lamp. Resistance — 249 ohms.

E. M. F.	W.	C. P.	L.	$\frac{L}{W}$	$\frac{L}{C.P.}$
63.0	25.4	0.3	0.42	0.016	1.61
74.6	37.8	1.0	0.77	.021	0.79
85.4	52.5	2.5	1.96	.037	0.78
99.0	72.2	6.3	4.30	.059	0.68
116.0	102.0	15.2	7.38	.072	0.49

Lamp C.

Weston 16 c. p. Cold resistance — 402 ohms.

E. M. F.	W.	C. P.	L.	$\frac{L}{W}$	$\frac{L}{C.P.}$
72.0	21.6	0.4	0.46	0.021	1.27
87.4	33.5	1.5	1.10	.033	0.76
102.0	47.8	4.4	2.09	.044	0.48
117.0	66.1	10.7	3.19	.048	0.30

Lamp D.

Weston 16 c. p., 70 volt. Resistance — 152 ohms.

E. M. F.	W.	C. P.	L.	$\frac{L}{W}$	$\frac{L}{C.P.}$
43.0	25.8	0.5	0.53	0.021	1.06
50.7	36.0	1.6	0.97	.027	0.62
60.5	52.0	5.2	2.03	.039	0.39
67.5	65.5	11.0	3.95	.060	0.36

Lamp E.

Bernstein 8 c. p. Resistance — 11,3 ohms.

E. M. F.	W.	C. P.	L.	$\frac{L}{W}$	$\frac{L}{C.P.}$
12.2	25.2	0.2	0.20	0.008	1.00
13.4	30.8	0.5	0.41	.013	0.84
15.0	40.4	1.3	0.75	.018	0.57
16.4	53.2	4.1	2.03	.038	0.50

It is interesting to compare these results with some obtained by still another method. Captain Abney and Colonel Festing in the Proceedings of the Royal Society have described a series of elaborate studies of the radiation of the incandescent lamp. The portion of their very important investigation, which has a bearing upon the efficiency, deals with the exploration of the spectrum of the lamp, under various degrees of incandescence, by means of an exceedingly sensitive thermopile. The energy of the visible spectrum of most sources of light is so minute that it has generally been deemed impracticable to measure it in this way. Captain Abney and his co-worker have, nevertheless, secured measurements covering not only the extensive regions of the so-called heat spectrum lying inside the red, but also the shorter wave lengths which constitute the visible spectrum. Their results are shown graphically in Fig. 3.

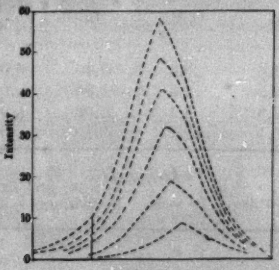

FIG. 3.

One of the British Electric Co's lamps was subjected to measurement in six different states of incandescence, corresponding to 33.6, 60.2, 93.8, 116.4, 130.8 and 150.5 watts respectively. The curves show the intensity of each wave length of the spectrum when the above amounts of energy were expended in the filament, and the total area inclosed by each curve affords a relative measure of the total radiation of the lamps in the state of incandescence in question. I have added to this diagram, of which, in other respects, Fig. 3 is a faithful reproduction, the vertical line lying between scale divisions 5 and 6 of their scale. This line marks the boundary between the visible and invisible spectrum. The entire area to the right of that line represents the energy wasted in the lamp; the much smaller area to the left comprises

the light-giving rays. The ratio of the entire area of each curve to that portion lying within the boundaries of the visible spectrum gives us the efficiency of the lamp for the state of incandescence produced by the expenditure of the number of watts for which the curve is drawn. This ratio increases from a very small value with the brightness of the lamp.

I have made approximate integrations of the areas embraced by the curves for 150.5 and 130.8 watts, respectively, for the purpose of comparing the efficiency thus calculated with the results obtained by Mr. Merritt. The ratios are :—

Watts.	Efficiency.
150.5	5.55 per cent.
130.8	5.15 "

The corresponding values for lower states of incandescence are all smaller than the above.

It will be seen that these results are in complete agreement with those obtained with the glass calorimeter and by the method of Melloni. We have, indeed, reason to feel that our knowledge of the absolute efficiency of the incandescent lamp, in so far as it can be expressed by the ratio of luminous to total radiation is well grounded, and that we are in position to determine the light-giving efficiency of any type of glow lamp in any condition of incandescence with the same certainty and exactness which is attainable in the measurement of other machines for the transformation of energy.

The average net efficiency of the incandescent lamps of to-day, for we may leave untouched for the present the efficiency of the processes by which the latent energy of fuel from which the current is generated has been converted into electrical energy, is rather below, than above five per cent; and since the ratio of total radiation to light-giving radiation increases but slowly as the temperature of the radiating body rises, the efficiency is not likely to be increased in any very marked degree until we shall have learned how to suppress altogether these long wave lengths which yield us dark heat, and are able to limit the vibrations of our source of light to that brief octave which comprises the wave lengths to which alone the human retina responds.

Whether this great step is to be made by robbing the glow-worm and fire-fly of their secret, as has been suggested in a recent address by the director of the Sibley College of Mechanical

Engineering[5] or by development along the lines sketched the other evening by Professor Brackett at the meeting of the Electric Club, or by the application of some principle as yet unconceived, we know not. Meantime, we have in the methods of artificial lighting of to-day abundant material for study and investigation.

The investigation of the efficiency of the arc light by the methods under consideration, is a much more difficult matter than the same determination in the case of the incandescent lamp. The radiating surface of the latter is very nearly of the same temperature throughout, and the ratio of total radiation to luminous radiation, obtained for the bundle of rays sent out in a single direction, gives us at once the measure of the efficiency. In the arc we have, however, a light-giving area of great brilliancy in the immediate neighborhood of the arc, and the temperature of the carbons falls with great rapidity from the maximum at the point and crater to regions which are at a red heat.

The entire light-giving area is included between the line surrounding the positive carbon, which is at red heat, and the corresponding line upon the negative carbon. Between these two lines we pass rapidly through regions, the light from which varies with the degree of incandescence by insensible gradations from that which a red hot surface is capable of emitting to that coming from carbon at the highest temperature which that substance can be made to assume. Now, the curve of distribution of candle-power taken in a vertical plane is, as we all know, a very peculiar one, and if we place our thermopile with alum cell interposed to measure the energy of the light-giving rays, the amount of radiation received upon the face of the pile will greatly depend upon the position in which the apparatus is set up. At an angle

[5] "The second of these greatest of inventors is he who will teach us the source of the beautiful soft-beaming light of the fire-fly and the glow-worm, and will show us how to produce this singular illuminant, and to apply it with success practically and commercially. This wonderful light, free from heat and from consequent loss of energy, is nature's substitute for the crude and extravagantly wasteful lights of which we have, through so many years, been foolishly boasting. The dynamo-electrical engineer has nearly solved this problem. Let us hope that it may be soon fully solved, and by one of those among our own colleagues who are now so earnestly working in this field, and that we may all live to see him steal the glow-worm's light, and to see the approaching days of Vril predicted so long ago by Lord Lytton."—ROBERT H. THURSTON—*Transactions of the American Society of Mechanical Engineers*, 1881, *p.* 22.

of 45 degrees, or 50 degrees below the horizontal plane, for instance, the amount indicated will be five or six times greater than in the horizontal plane. Now, the surface of total radiation is much larger than that from which the light-giving rays emanate. It includes, in addition to the incandescent surfaces near the arc, all those portions of the carbons which are heated, either by conduction or by the current.

The amount of heat radiated from regions which are below the red heat is very considerable, and forms an important factor in the determination of the efficiency. Were the distribution of total radiation in the vertical plane identical with that of the light-giving rays, the measurement of their ratio with the axis of the thermopile in any plane which passes through the arc, would give us the efficiency of the lamp; but the curve of distribution of total radiation is not the same as that of candle-power, and the ratio in question is a function of the plane which the axis of the pile makes with the horizon. It becomes necessary, therefore, to make an exploration of the entire zone through which the lamp sends out rays, determining the ratio of total to luminous radiation for each angle, and then to integrate the results. Such an investigation is now in progress under my direction, and Mr. H. Nakano, who is carrying on the experiments, has reached some exceedingly interesting results. The research will soon be ready for publication in its complete form, and it will afford us much more definite data concerning the radiations of the electric arc than we now possess. It will not be out of place even now to say a word concerning the method which is being employed, and the general character of the results already obtained.

The first measurements were made by the second method employed by Mr. Merritt, the thermopile in the horizontal plane. The lamp subjected to measurement was of the long arc type, with 9 amperes of current and 45 volts. The efficiency in this plane was found to be surprisingly small. It was found, moreover, to vary in marked degree with the diameter of the carbons used, increasing as the diameter decreased to the point at which the carbons were rendered hot by the current, when, as might be expected, it fell off again.

The lamp was then mounted in a frame which also carried the thermopile and alum bath, and which was so constructed that measurements could be made at any desired angle. All necessary changes of angle could be made without varying the distance

from the arc to the face of the pile, or the relation of the alum bath to the latter. By means of this apparatus, which is shown

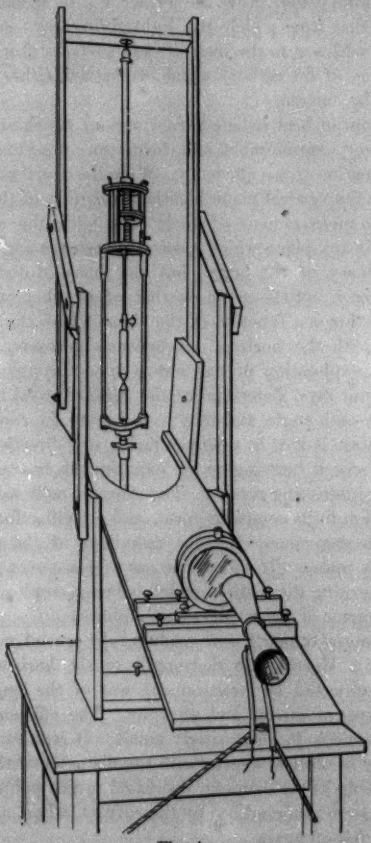

Fig. 4.

in figure 4, it has been found possible to determine the ratio of total to luminous radiation throughout the zone of radiation of the lamp, and to plot the curve of distribution of each.

Without entering into the details of an incompleted research, I may indicate the general character of the results by means of a diagram. The curves shown in figures 5 and 6 are those relating to a "long-arc" lamp with carbons .45 inch in diameter. They represent respectively the distribution of luminous and total radiation emanating from the lamp. The radii show the positions

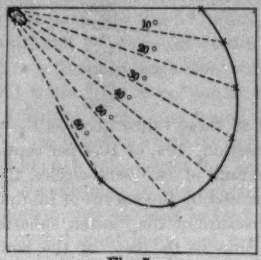

Fig. 5.

for which measurements were taken; distances measured along these lines from the origin to each curve give the relative intensities of light-giving and total heat energy in each position.

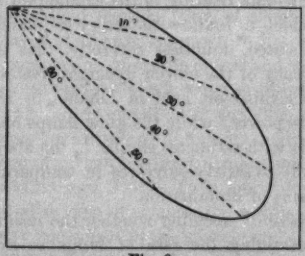

Fig. 6.

The curve of luminous radiation corresponds in form with that of candle-power. The distribution of total radiation, however, differs widely from these, and the ratio, $\frac{\text{luminous energy}}{\text{total energy}}$, is a function of the angle which the line of measurement makes with the horizontal plane. The values of the efficiency in the case in question for the various angles at which measurements were made, are given in table iii. They form the basis for the curve in figure

6, which is the diagram of efficiencies of the arc light under the conditions of operation already stated.

TABLE III.

Efficiency of an arc lamp; after measurements by Mr. H. Nankano.

Angle.	Efficiency. — Luminous radiation. / Total radiation.
0°	.0548
10°	.0901
20°	.1228
30°	.1506
40°	.1552
50°	.1039
60°	.0676
63°	.0492

The integration of these values gives as the mean efficiency of the arc lamp in question, .104, or 10.4 per cent.

The ratio of the radii of two semi-circles, the areas of which equal the areas inclosed by the curves of luminous and total radiation, gives us a measure of the "mean spherical" efficiency of the lamp. This ratio in the case of the lamp to which these curves refer is very much smaller than the generally accepted values of the efficiency of arc lamps, expressed in terms of the candle-power per watt, would lead us to expect. The intensity of the arc is, however, seldom expressed in mean spherical candles, and there are few data relating to the candle-power of this source of light upon which to found satisfactory estimates. On the one hand we find it stated, doubtless correctly, that the mean light-producing efficiency of the eleven dynamos, tested at the International Health Exhibition, held in London in 1884, was 1,440 candles per horse-power,[6] while the glow lamps only yielded 175 candles, and it is with estimates similar to the above with which we have generally to satisfy ourselves in comparing arc and incandescent systems of illumination.

For the purpose of deciding whether the results of Nakano's method of determining the ratio of luminous to total radiation are compatible with our other sources of knowledge concerning the arc light we must make use of mean spherical candle-power as our basis of comparison.

Very careful measurements of the mean spherical candle power of two arc lamps of representative and successful commercial types were made in the physical laboratory of Cornell University,[7]

[6] Julius Maier, Arc and Glow Lamps, p. 52.

[7] *The Photometry of Arc Lights.* Thesis by Benjamin W. Snow, 1885. MS. in the Library of Cornell University.

following the method of the Franklin Institute Committee. Both of these lamps were rated at 2,000 c. p. They were maintained by dynamos of the types for which they had been especially designed, working under normal conditions. One of the lamps gave a mean spherical candle-power of 295, when working in series with nine other lamps of the same construction. When placed in circuit alone, the candle-power rose to 348. The energy expended in the lamp in each case was 550 watts, and the efficiency accordingly 1.8 watts and 1.6 watts per candle.

The other lamp was found to reach 609 mean spherical candles at the cost of 601 watts. An inspection of the result obtained by the Franklin Institute Committee would lead us to regard these as extreme values, between which the performance of almost all arc light would lie, as a rule, nearer the lower than the upper of these limits. The efficiency of arc lights, then, expressed in mean spherical candle-power per watt is frequently as low as 1.5 times that of the incandescent lamp, and, rarely, three times as high. Now the mean efficiency of the arc lamp under discussion, *i. e.*, the ratio, $\frac{\text{luminous radiation}}{\text{total radiation}}$, according to the measurements of Mr. Nakano, is almost exactly 10 per cent. The efficiency of incandescent lamps, defined in the same way, according to Mr. Merritt, may, as we have seen, be taken at about 5 per cent. The ratio is 2:1 in favor of the arc lamp, which lies within the limits determined by comparison of candle-power and watts.

Small as these values for the efficiency of the electric light are, they show marked improvement over the efficiency determined in a similar manner for sources of illumination which depend upon the incandescence of carbon by direct combustion. More than a quarter of a century ago, Julius Thomsen[1] presented before a gathering of Swedish men of science, the results of an investigation of the energy consumed in the sperm candle, and in various oil and gas flames. His memoir bore the suggestive title of the Mechanical Equivalent of Light, and is one of the earliest contributions to our knowledge of the energy of luminous radiation.

The instruments employed in Thomsen's experiments were the thermopile and galvanometer, the indications of which were reduced to absolute measure by determination of the deflection

[1] Julius Thomsen: Das Mechanische Æquivalent des Lichtes; *Poggendorff's Annalen*, Bd. 125, p. 348.

produced by the radiation from a glass globe filled with hot water. The total loss of heat by radiation which this globe sufferred was calculated from its rate of cooling, using Dulong and Petit's law. The water equivalent of the globe was 1,351 grains; its total loss of heat per minute at 50 degrees C. was 250 calories; its loss of heat by radiation at the above temperature, when the air of the room was at 17 degrees, was 102 calories per minute. Under these conditions the influence of the globe of water upon the thermopile placed at a given distance was observed. A luminous body having been substituted for the globe, its influence on the pile was likewise noted, and its total radiation in calories calculated by comparison of the deflections produced in the two cases.

For a sperm candle burning 8.2 grains per hour, the total radiation estimated by this method was 210 calories per minute. Other flames gave out quantities of heat nearly in proportion to their candle-power, as will be seen by inspection of table iv.

TABLE IV.

Calories per candle-power radiated by various flames, according to Julius Thomsen.

Source of Illumination.	Candle-power.	Calories per candle.
Sperm candle.....	1.	210
Gas flame.....	1.2	201
Gas flame.....	7.7	199
Moderator lamp.....	8.6	199

The luminous energy was obtained by a method similar to that pursued by Merritt in the experiments already described. A bath containing a layer of water 20 cm. in thickness was interposed between the lamp and the thermopile and the indications of the galvanometer noted. The results were based upon the assumption that the cell absorbed 13 per cent. of the light and all of the dark rays. This estimate is doubtless faulty, and may involve a reduction of several per cent. from the values given by Thomsen. His results, uncorrected, are as follows:—

TABLE V.

Energy of luminous radiation of various flames in calories, according to Julius Thomsen.

Source.	Candle-power.	Luminous Energy per. c. p.
Candles.....	1.	4.4 calories.
Moderator lamp....	6.25	3.9 calories.
Moderator lamp....	8.6	4.1 calories.
Gas.....	7.7	4.2 calories.
Gas.....	1.2	3.7 calories.

The energy of the light-giving rays per candle-power of light produced is then, according to Thomsen, very nearly the same for the flames of the candle, oil lamp and gas burner. This conclusion has been abundantly confirmed by spectro-photometric observations of the quality of the light which they emit. It appears, moreover, from these observations, of which I shall have occasion to speak at length presently, that the temperature of the incandescent particles in such flames agrees very closely indeed with that of an incandescent lamp, consuming 5 watts at 16 c. p, being, as a rule, lower, rather than higher, than the latter; and the calculation of the energy of such a lamp in calories per minute, making use of the data furnished us by the investigation of Abney and Festing, or of Merritt, affords most satisfactory evidence of the accuracy of Thomsen's results. Let us take for example the case of an incandescent lamp in which 5 watts per candle-power are expended, and in which the ratio

$$\frac{\text{Luminous radiation}}{\text{Total radiation}} = .05.$$

The energy converted into light in such a lamp is .25 watt. Now,

$$1 \text{ gramme-calorie} = 4.2 \times 10^7 \text{ ergs.}$$

$$1 \text{ watt} = 10^7 \text{ ergs} = \frac{1}{4.2} \text{ gramme-calories per second.}$$

$$.25 \text{ watt} = \frac{.25 \times 60}{4.2} \text{ gramme-calories per minute,}$$

and the heat equivalent of the luminous energy is 3.6 gramme-calories per minute.

This value is somewhat smaller than those given by Thomsen in the preceding table, but proper corrections for the diathermancy of the water bath used in his experiments and for the difference in standards of candle-power—the light given by his sperm candle being slightly in excess of the legal standard of the present day—will bring the two into excellent agreement.

The entire energy developed by the chemical reactions occurring in these flames per candle-power of light produced were, however, about 1,400 calories in the case of candle and oil lamps, and 4,100 calories in the case of gas, so that the gross efficiency would be respectively 0.3 per cent. and 0.1 per cent. The average ratio of total radiation reaching the thermopile, to luminous radiation is about .2 per cent., but this ratio cannot be considered in the same light as that obtained in the case of the incandescent lamp, since

a gas or oil flame is in reality a column of heated vapor containing particles of unconsumed carbon, which reaches far above the luminous region, sending out dark rays from its upper and cooler portions, which do not reach the face of the thermopile at all. The relation which the total radiation of this heated column bears to the heat dissipated by convection cannot be determined, and the determination of total radiation from the light-giving portions alone is of little value. It is only in the matter of gross efficiency, therefore, that we can institute a comparison between electric lamps and the older methods of illumination, and the gross efficiency of the former depends upon the efficiency of production of electric current. Under conditions, such that 10 per cent. of the total energy of the fuel consumed is converted into electricity—conditions, which are, I believe, rarely attained by our present methods—the gross efficiency of an incandescent lamp, of which the net efficiency, determined by the methods which I have already described, is 5 per cent., would be 0.5 per cent.; a value which is five times greater than that of a lamp burning the kind of gas used by Thomsen, and which stands in the ratio of 5:3 (or, probably, rather more than that) to the gross efficiency of an oil flame. These flames must, of necessity, vary very widely with the quality of the fuel consumed, and with the condition under which combustion is maintained.

If we apply a similar method of computation to the values given by Mr. Preece in his recent address at the Bath meeting of the British Association for the Advancement of Science,[9] assuming that the conditions under which each illuminant is consumed are such that the temperature of the incandescent carbon equals that which is maintained in the filament of an incandescent lamp at 5 watts per candle, with a net efficiency, as before, of 5 per cent., a set of conditions which can be attained in practice only in the most perfectly constructed oil and gas lamps, and which are fulfilled in many of the best of our incandescent lamps of to-day, we obtain the following results:—

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[9] Preece. Address before Section A, meeting of the B. A. at Bath, 1888. *Nature*, vol. 38, p. 496.

Table VI.

Gross efficiency of various illuminants deduced from the values given by Preece. The heat equivalent of the luminous radiation of a candle is assumed to be 3.6 gramme-calories per minute.

Illuminant.	Watts per candle. (Preece.)	Gramme-calories per minute per candle.	Luminous radiation. / Total energy = gross efficiency.
Tallow.....	124	1770.	.00203
Wax.	94	1340.	.00268
Sperm	86	1230.	.00293
Mineral oil ...	80	1143.	.00315
Vegetable oil..	57	815.	.00442
Coal gas	68	971.	.00317
Cannel gas ...	48	685.	.00521

In considering these values it should be borne in mind that coal-gas is a fuel which has been obtained by the previous expenditure of considerable energy. Were we to take as our basis the consumption of coal necessary to the production of a candle-power of light, instead of the heat of the combustion within the gas flame itself, the values for the efficiency of coal-gas as an illuminant would be very considerably reduced.

We have already seen that there are excellent experimental grounds for the statement that the gross efficiency of the incandescent lamp is about .005, and that of the arc lamp about .01, under the assumption of the waste of 90 per cent. of the total energy of the fuel in the various processes leading to the production of the current, and that the latter figures, small as they are, are considerably in excess of the gross efficiency of candles, oil or gas. We are in possession, moreover, of the means of expressing exactly the degree of superiority which the electric light possesses over those illuminants in the important matter of the heating effect upon the surrounding atmosphere. Gas and oil flames deliver in the neighborhood of 1,000 gramme-calories of heat per minute to the room for each candle-power, of 3.6 gramme-calories of luminous radiation. An incandescent lamp of 5 per cent. net efficiency delivers only 72 gramme-calories per candle-power.

The net efficiency of the incandescent lamp may be raised somewhat by increasing the temperature of the carbon filament, and, indeed, it has already been somewhat raised by the introduction of the new "3 watt" lamps. These lamps have been excluded from this discussion because we have as yet no complete data with reference to them, and because it seemed desirable,

aside from that, to institute comparisons between sources of illumination in which the degree of incandescence was the same, and for all of which, consequently, candle-power had the same meaning.

When we raise the temperature of our source of light, however, we introduce changes, of which the methods thus far considered take no cognizance.

In increasing the degree of incandescence, the ratio of luminous energy to total energy of radiation is slowly increased, and at the same time the relative brightness of the various rays which constitute the visible spectrum changes. In a word, the *quality* of the light changes, and we are confronted by important variations which cannot be expressed in candle-power.

The investigation of these changes in composition, upon which color depends, involves the study of the visible spectrum of the source of light and the comparison of its intensity, wave length for wave length, with the spectrum of some properly chosen standard. The instrument necessary to this work is the spectro-photometer, by means of which the spectra of the two lights to be compared are brought together in the field of view, one above another, like wave lengths everywhere in the same vertical line. The measurements consist in bringing the two spectra to the same intensity in each of the regions selected for observation successively, and in determining the amount by which it is necessary in each case to reduce the intensity of the brighter. A variety of devices have been made use of for varying the brightness of the spectra, and the standards of comparison adopted by different observers have included the candle, the petroleum flame, the gas flame, and the incandescent lamp, maintained at a constant voltage. Thus W. H. Pickering[10] obtained the necessary range of intensities by placing the lamp under inspection upon a slided carriage and varying its distance from the slit of the spectroscope. His standard of comparison was a gas flame. H. C. Vogel[11] used as his standard a petroleum flame. Crova,[12] who brought the intensities of the two spectra to equality by means of a polarizing device, adopted the moderator lamp as a standard. Otto Schumann, in

[10] W. H. Pickering, *Proceedings* of the American Academy of Arts and Sciences, vol. 15, 1880.

[11] H. C. Vogel, *Berliner Monatsberichte*, 1880, p. 801.

[12] A. Crova, *Comptes Rendus*, 87, 1878, p. 322.

his study of the incandescent lamp, made use of a "benzine" candle. The intervention of a revolving disc with open and closed sectors and of wedges of smoked glass have also been applied to the regulation of the intensity, and the method of varying the width of the slit itself, a device due to Vierordt, has been found to give good results, where the range of intensities was inconsiderable.

The methods of presenting the results of this class of measurement have differed as widely as the methods of observation and the choice of standards; but it is possible wherever the data are properly given and the character of the standard is known, to reduce them all to a common basis of comparison. When thus reduced these measurements are found to agree in all essential particulars, and they afford us very definite knowledge of the

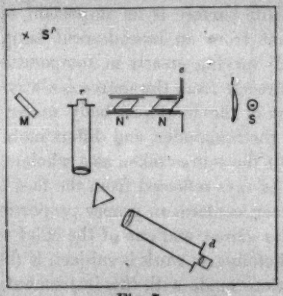

Fig. 7.

character of the light emitted by the sources of illumination to which the spectro-photometer has been applied.

Figure 7 shows the form of the spectro-photometer recently used by Mr. W. S. Franklin and myself in an extended series of observations upon artificial sources of illumination and in the comparison of their spectra with that of daylight.

To the slit of a one prism spectroscope are attached a set of total reflection prisms, *r*, by means of which rays may be introduced into the upper and lower halves of the slit, these rays coming respectively from sources of illumination placed to the right and left-hand in a line at right angles to the axis of the collimator tube. The standard of illumination, which is an incandescent lamp s, maintained at 16 candles, is placed at the observer's right hand.

Its rays, having been rendered parallel by means of a condensing lense, *l*, pass through a pair of Nicol's prisms, N and N′, the first of which is free to revolve, and enters the upper half of the slit. The intensity of the spectrum of this lamp can be reduced at will by the rotation of the first Nicol, and its brightness is calculated from the angle between the flames of polarization of the two Nicols. To the left of the slit is mounted a block of magnesium carbonate, its face vertical and forming an angle of 45 degrees with the axis of collimation of the spectroscope. The rays of the source of light to be investigated, s′, which is placed at a convenient distance, fall upon the magnesium carbonate, and it is such of the diffusely reflected rays from the latter as reach the total reflection prisms, and thus enter the lower half of the slit, which form the second spectrum. The object gained by the interposition of this white surface is an important one. All artificial light, except that from an incandescent lamp, emanates from glowing materials varying greatly in temperature, and the spectrum obtained directly from the source is always that due to some particular portion of the luminous body under investigation, to the exclusion of the remainder, and differs more or less in character from that of the source taken as a whole.

The spectrum of rays reflected from the face of the magnesium carbonate, however, contains in proper proportions the light from all portions of the source, and one of the chief sources of error to which spectro-photometric work is subject, is thus eliminated.

The investigations made with this instrument, which have been described in a paper read before the American Association,[13] included the measurement of candle flames, and of various petroleum and gas lamps, also of the lime light, the incandescent lamp under a wide range of conditions, of the electric arc and of daylight by clear and by clouded sky. The results obtained illustrate the precise character of those differences in composition to the bearing of which, upon the study of the efficiency of artificial illumination I desire to call your attention.

In the first place it was found that the light of the candle, and of oil and gas flames, although subject to considerable fluctuations from variations of the condition under which combustion occurs,

[13] Edward L. Nichols and W. S. Franklin. A Spectro-photometric Comparison of Artificial Sources of Illumination. Paper read before Section B; A. A. A. S. at the Cleveland meeting, August, 1888.

differ but slightly in quality from each other and from that of incandescent lamps maintained at normal candle-power. The incandescent material in all is carbon; and it is a significant fact that the average temperature of incandescence is nearly the same in all luminous flames, and that the highest temperature, until very recently at any rate, at which it has been found practicable to maintain the carbon filament of the glow-lamp, is very nearly that at which the same material exists under the most favorable conditions in oil and gas flames. Hence it is that the radiant

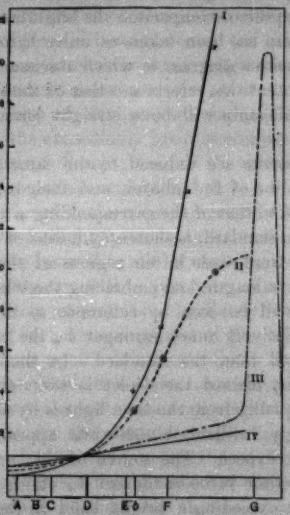

FIG. 8.

energy per candle-power, as has been shown by Julius Thomsen, is nearly the same for all these flames.

Passing to other sources of illumination, such as the lime light and the electric arc, we find the entire portion of the spectrum lying beyond the yellow increasing more rapidly, regions of longer wave length than the yellow increasing less rapidly than the candle power; the rate of increase growing steadily as the wave length diminishes from the red to the violet end of the spectrum. Fig. 8 shows the results of comparisons of the spectra of the lime light, electric arc, and of daylight, by clear and by unclouded

sky, with that of an incandescent lamp maintained at its normal candle-power. This lamp, which was chosen as a standard of comparison, was an Edison 16-candle, 100 volt lamp. Its light was precisely similar to that of a "Board of Trade" argand gas burner, showing the same relative brilliancy throughout the whole of the visible spectrum. The measurements were made with the spectro-photometer just described (see Fig. 7), the light in every case falling upon the block of magnesium carbonate, and entering the slit of the spectroscope after reflection from the face of the latter. For purpose of comparison the brightness of the standard incandescent lamp has been taken as unity throughout the spectrum. If we make a diagram in which abscissæ are wave-lengths and ordinates, intensities, referred to that of the standard as unity, the curve for this lamp will be a straight horizontal line, with ordinate = 1.

All other spectra are reduced to the same brightness in the region of the D line of Fraunhofer, and their brightness in other regions, referred to that of the corresponding wave lengths in the spectrum of the standard, is shown by means of curves.

Observations were made in ten regions of the spectrum, equidistant as to wave length, and embracing the whole of the visible spectrum. It will be seen by reference to the figure that the lime light is relatively much stronger in the violet and much weaker in the red than the standard. In the arc light this increase of intensity toward the violet is even more marked, but its variation in quality from the lime light is by no means so great, as its exceedingly brilliant, bluish-white appearance to the eye would lead us to expect. The source of that appearance and of the very high actinic value of the arc is found, however, in the presence of an exceedingly bright band in the extreme violet. Here the relative intensity of the arc light spectrum rises abruptly about 3 to 20 times that of the incandescent lamp.

Measurements were made upon a long arc lamp with ½ inch carbons, with 10 amperes and 50 volts and a short arc lamp with a 20 ampere current. The character of the light was found to be almost identical excepting in this light band in the neighborhood of the G line, which is much more prominent in the long arc lamp. The character of the light was found to be much the same at all angles below the horizontal plane.

The only other spectrophotometric measurements of the electric arc with which I am acquainted, have been made upon the

Foucault regulator, a lamp with carbons of small diameter. Fairly concordant determinations of the distribution of intensities in the spectrum of this lamp by W. H. Pickering,[14] H. C. Vogel,[15] and Crova,[16] show that the light of this lamp is decidedly bluer than that of the lamps with large carbons in vogue at the present day; the spectrum of the former being about five times as rich in the violet as that of gas or oil flames. Mr. Nakano's results, of which mention has already been made, indicate marked increase in the efficiency of the arc lamp, as the diameter of the carbons is decreased; and since increase of efficiency arises from a higher average degree of incandescence, we should expect just such an increment in the shorter wave lengths as shows itself in the case of the Foucault regulator.

Finally, in the case of daylight we find the intensity of the shorter wave lengths exceedingly great as compared with that of any artificial source of illumination. If the spectrum of daylight be brought into comparison with that of an incandescent lamp, and the two be reduced to the same intensity in the yellow, the extreme red of the daylight spectrum will be so *dim* in comparison with that of the lamp as to render measurements difficult. In the violet the discrepancy will be just as marked, the sun's spectrum being relatively of enormous brilliancy. Curve i., Fig. 8, shows the result of such a measurement of the daylight spectrum, taken just after noon upon a cloudless summer day.

Vogel has given data of a determination in which the preponderance in the violet was even more marked, the relative intensity of daylight for the region corresponding to wave length, 4,260 (just beyond the G line), being 100 : 1 for spectra which were equally bright in the neighborhood of the D line.

Ordinarily, there is considerable absorption of the blue and violet by moisture in the atmosphere, and a measurement of daylight under a densely clouded sky gave curve ii. Even under these conditions, with the violet reduced to about one-tenth of the value which it possesses in clear weather, daylight is very much bluer than any artificial light. The light emitted by burning magnesium approaches more nearly to it than any other, being, according to Pickering, considerably stronger throughout the blue and violet than the light from the Foucault arc lamp.

[14] W. H. Pickering, *l. c.*

[15] H. C. Vogel, *l. c.*

[16] A. Crova, *l. c.*

Its color, however, is not reinforced by a violet band like that in the spectrum of the electric arc, a region which, by its extraordinary brightness, has marked influence upon the color of the light.

These variations depend upon temperature primarily, and they

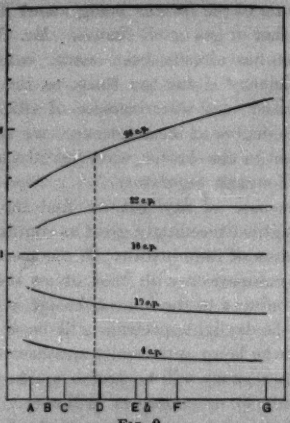

FIG. 9.

may be studied to the best advantage in the spectrum of the incandescent lamp. The radiating surface of such a lamp is at a nearly constant temperature throughout, and it may be given a very considerable range in the matter of incandescence, involving variations in color and total intensity, which are under complete control.

An Edison lamp, similar to that which had been used as a standard in our previous measurements, was subjected to spectrophotometric analysis by Mr. Franklin and myself, at 4 candles, 10 candles, 16 candles, 22 candles and 28 candles, successively. The results obtained are shown in figure 9.

The spectrum of the lamp at 16 candles is taken as of unit brightness throughout, and the other curves show the amount of light of each wave length emitted by the lamp in the above-mentioned states of incandescence. Intensities, in every case, are referred to the light of corresponding wave length, given by the same lamp at 16 candles, as unity.

At the red end of the spectrum the intensity increases more

slowly than candle-power; at the violet end more rapidly. There exists an intermediate wave length for which the brightness is proportional to the candle-power. The vertical line in the diagram shows the portion of the spectrum for which this holds true, a point in the yellow at wave length 6,000.

If we suppose the same measurements executed upon a set of lamps in every respect similar to the one in question, excepting that their radiated surfaces are of such size that they give 16 candles, as indicated by the Bunsen photometer when the degree of incandescence corresponds respectively to that at which the lamp actually measured emitted at 4, 10, 16, 22, and 28 candles, there would result a set of curves of the same general character as those in Fig. 12. At wave length 6,000 these curves would have a common value, and they would serve to indicate both the quantity and quality of the variation of the carbon filament, as a function of the incandescence, candle-power remaining constant. The form of these curves is shown in Fig. 10. They afford us data for discussion of the candle as a standard of illumination

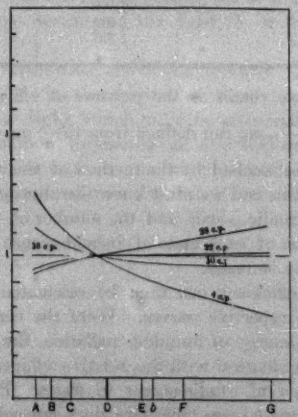

FIG. 10.

which could not be obtained in any other way. They show the relative distribution of energy in the spectrum of five lamps, which, according to the indications of the Bunsen photometer, are of equal brightness, but which differ both in the quality and

in their total energy of their luminous radiation. Their efficiency expressed in terms of the candle-power produced per watt expressed in the lamp, rises rapidly as the incandescence increases. For lamps of the type upon which these measurements were made, for instance, the relative efficiency referred in each case to that of the lamp, the incandescence of which corresponds to that of an Edison lamp at 16 candles, is given in the column headed $\frac{\text{Candle-power}}{\text{Watts}}$ in table vii.

TABLE VII.

State of incandescence equivalent to that of an Edison 16-candle lamp, giving—	Relative efficiency referred to that of a 16-candle lamp as unity.	
	$\frac{\text{Candle-power}}{\text{Watts.}}$	$\frac{\text{Luminous radiation.}}{\text{Total radiation.}}$
(1) 4 candles	.394	.211
(2) 10 "	.729	.632
(3) 16 "	1.000	1.000
(4) 22 "	1.218	1.368
(5) 28 "	1.391	1.589

If, however, we retain as the measure of efficiency, the ratio, $\frac{\text{luminous radiation}}{\text{total radiation}}$, we can deduce from these curves values coinciding with those reached by the method of the thermopile and alum cell. To this end we must know the above-mentioned ratio for some one candle-power and the number of watts necessary to the production of each state of incandescence for which the computation is to be made.

The relative efficiency can then be calculated from the areas inclosed by the respective curves. Were the candle-power proportional to the energy of luminous radiation, the values thus obtained would be identical with the relative efficiency determined from the relation of candle-power to watts. The relative efficiency thus computed (see table vii.) does not coincide with that obtained from the ratio of watts to candle-power, however, for the reason that the various rays which make up the visible spectrum do not enter into the production of candle-power in proportion to their energy. The most important wave lengths, so far as light-giving power is concerned, are those which form the yellow

of the spectrum, and the relative luminosity falls off rapidly both toward the red and the violet. The longer wave lengths have, however, much more influence upon candle-power than the more refrangible rays, as will be seen by an inspection of the curves, the relative falling off of the red end of the spectrum being compensated by larger and larger accessions in the blue and violet as the state of incandescence increases.

Luminosity is the factor, which we must take into account in seeking a complete expression for the efficiency of any source of illumination, and the method to be pursued in the determination of the luminosity must depend upon the use to which the light is to be applied. If we estimate light by its power of bringing out the colors of natural objects, the value which we place upon the blue and violet rays must be very different from that which would be ascribed to them if we consider merely its power of illumination as applied to black and white. In a picture gallery, for instance, or upon the stage, the value of an illuminant increases with the temperature of the incandescent material, out of all proportion to the candle-power, whereas candle-power affords an excellent measure of the light to be used in a reading room.

A number of determinations of the luminosity of artificial light have been made. In the earliest of these by Vierordt,[17] the amount of white light which may be mixed with each color of the spectrum, without producing an appreciable change of tint, was taken as the measure of the luminosity of that color. The result is shown graphically in Fig. 11. The curve indicates the

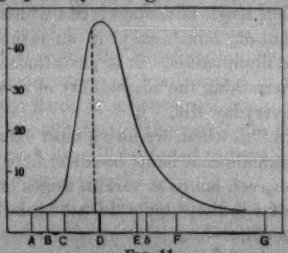

FIG. 11.

light-giving power of each wave length, estimated in the above manner. The source of light experimented upon was a petro-

[17] C. Vierordt, *Annalen der Physik und Chemie*, Bd. 137, p. 200.

leum flame. The vertical line indicates the region of the spectrum within which—according to the measurements of the quality of light of the incandescent lamp already described—the increase in the brightness of the spectrum is proportional to the candle-power. This region corresponds very nearly with that of maximum luminosity of the spectrum.

The luminosity of the blue and violet rays is so very small that in the production of *candle-power* the influence of the very rapid growth of this end of the spectrum with increasing temperature of the lamp is scarcely appreciable. If we estimate the light-giving value of the different portions of the spectrum by means of the facility with which we can distinguish black characters upon a white ground, the importance of the more refrangible rays is still farther diminished. Thus Macé de Lepinay and Nicati[18] have shown that if yellow and blue light, estimated to be of equal brightness by photometric means, are of such intensity that one can clearly distinguish a printed page when illuminated by the yellow, the same page will be entirely illegible, when the blue light alone falls upon it. These observers conclude, indeed, that "the mere distinguishing of objects is due almost exclusively to the illumination produced by the less refrangible half of the normal spectrum;" so that at equal brilliancy "the superiority of yellow sources of light (luminous gas flames, incandescent lamps) over sources richer in blue rays (light of the electric arc) is incontestible." "The only real advantage," they add, "upon the side of the light from the electric arc is when one desires to rehabilitate objects more nearly in the hues which they present in the light of day." This single advantage is one which it is impossible to take due account of, numerically, in an estimate of the efficiency of artificial illumination. It is, nevertheless, a most important factor in determining the adaptability of a light to nearly all the purposes of everyday life.

Otto Schumann,[19] to whom we owe a most exhaustive study of the light of the incandescent lamp, has determined the luminosity of several types of such lamps at various stages of incandescence. His results, in so far as they apply to a 16-candle Edison lamp, are given in table viii.

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[18] Macé de Lepinay and W. Nicati, *Journal de Physique*, second line, T. 2, p. 73, 1883.

[19] Otto Schumann, *Elektrotechnische Zeitschrift*, Bd. 5, p. 294, 1884.

TABLE VIII.

Luminosity of an Edison lamp of various stages at incandescence, according to Otto Schumann.

Amperes.	Volts.	Watts.	Luminosity of various regions of the spectrum.						
			Red —λ 676	Orange λ 656	Yellow λ 615	Green λ 557	Blue λ 487	Indigo λ 464	Violet λ 429
0.625	87.3	54.6	1.18	4.64	.....	20.14	0.64	0.11	.....
.678	90.4	61.3	1.68	6.66	.....	30.35	1.05	0.20	.....
.737	94.7	68.8	2.24	9.34	53.11	50.05	1.71	0.34	....
.748	97.4	72.9	2.59	10.92	63.28	62.33	2.28	0.47	....
.823	105.0	86.4	4.06	17.14	99.32	104.3	4.09	0.88	....
.944	112.9	106.7	6.97	28.85	163.0	189.1	7.88	1.75	.....
1.009	117.6	118.6	8.74	37.14	222.6	255.7	11.62	2.71	0.42
1.035	120.4	124.7	9.36	41.67	263.3	317.7	16.04	3.72	0.60
1.099	124.5	136.4	11.43	52.36	345.2	472.2	26.24	6.53	1.04

I have made these values of Schumann's the basis of a set of curves, by means of which the variation in luminosity, with total energy in watts, is exhibited (see Fig. 12). It will be seen that the position of the maximum moves slightly towards the violet as the brightness of the lamp increases. This tendency is very slight within the range of temperatures reached by the incandescent lamp. In the arc light we should find the displacement more marked, but in the case of sunlight, in which, as we have seen, the shorter wave lengths are in such preponderance, the movement of the maximum is inconsiderable. The curves shown in Fig. 13 are taken from the investigation by Crova, who has determined the distribution of luminosities in the spectrum of sunlight and of the flame of a petroleum lamp. The maximum in sunlight is at λ— 582, that of the petroleum λ— 592. Nearly all sources of illumination will be found to have a maximum lying between these two wave lengths.

A comparison of the total luminosity of the incandescent lamp with its candle-power shows that the former increases with the energy of the lamp more rapidly than the latter, although the discrepancy is not so marked as in the comparison of efficiency of candle-power with that of luminous radiation.

The following table, obtained by the summation of the luminosity curves, shows the relation between candle-power and

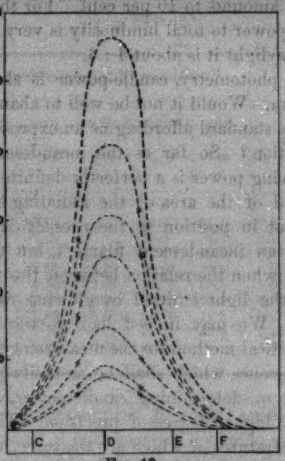

Fig. 12.

total luminosity, in the case of the lamp studied by Schumann:—

Table IX.

Candle-power and total luminosity of the incandescent lamp.

Watts.	Candle-power.	Total luminosity.
54.6	.....	4.11
61.3	.....	6.31
68.8	10.12	10.30
72.9	12.05	12.58
86.4	18.80	20.64
106.7	31.60	36.80
118.6	41.44	49.77
124.7	50.16	60.85
136.4	64.15	.....

Plainly then, candle-power does not afford a measure either of the light-giving energy or of the luminosity of a source of illumination. When used in the comparison of sources which differ in temperature, the indications of the photometer always yield us relatively too low a value for the intensity of the lamp of higher incandescence. In the case of candles *vs.* gas, or of either of these in comparison with the incandescent lamp at nor-

mal temperature, the error is not important, but between the candle and the "16-candle" lamp maintained at 50 candle-power, the discrepancy amounts to 10 per cent. For the electric arc the ratio of candle power to total luminosity is very nearly 4 : 5, and in the case of daylight it is about 4 : 6.

In arc light photometry, candle-power is already a well-nigh meaningless term. Would it not be well to abandon it altogether in favor of some standard affording us an expression for the luminosity of radiation? So far as the incandescent lamp is concerned, light-giving power is a perfectly definite function of the temperature and of the area of the radiating surface. We are unfortunately not in position at the present day to measure the temperature of an incandescent filament, but the time will undoubtedly come when the relation between the temperature and the quality of the light emitted by glowing carbon will be definitely known. We may indeed look forward to the development of some optical method for the measurement of the temperature of incandescence which shall be as easily performed as our present method of determining candle-power, and which shall admit of a much higher degree of precision. The comparison of lamps, the temperatures of which are the same, will then reduce itself to a question of radiating surface. Total luminosity and total energy of luminous radiation, per unit of surface, together with net and gross efficiency, may then be expressed, in so far as incandescent carbon is our source of illumination, as functions of

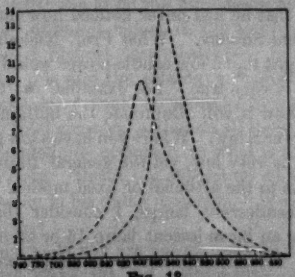

FIG. 13.

the temperature alone, and the performance of any lamp may be defined in terms which admit of no uncertainty.

DISCUSSION.

THE CHAIRMAN:—Gentlemen, I am sure that you must have heard with the greatest pleasure the very able paper that has been read extemporaneously—if I may so express it. I have the paper before me, and I think that such a subject should incite us to a very full and free discussion. We have with us this evening a number of gentlemen who are interested in this question, either from a scientific or commercial standpoint, and a great many of them have already had some practical experience with regard to the fact that candle-power does not express the light-giving capacity of a lamp, and they have had some little difficulty in convincing city councils and other bodies of that fact. I think that such members should take an active part in the discussion, and I do not propose to stand in their way by occupying your attention longer.

MR. UPTON:—I listened with great pleasure to the paper of Prof. Nichols. I think that we have heard a paper which puts more clearly than it has ever been put before, the subject of candle-power. For the last few years there has been considerable discussion regarding candle-power. It is a matter which enters very largely into my business; and speaking of the difficulty of making good measurements, and of the meaning of candle-power, I might mention a story concerning a young gentleman whom many of you know, who was engaged to be married. He went out into the country and spent Sunday there, and, on coming back, innocently remarked that he had never noticed how much light a lantern gave until that Sunday. What Prof. Nichols has said as to the amount of light that a low candle-power would give for illuminating purposes is very true. For example, you take a fire, and you will notice how it will illuminate the buildings around, and yet the candle-power is low. Where you have a low glow from coal, the candle-power is very low, yet the general illuminating power is very large. As to the artificial or fixed method of rating candle-power in incandescent lamps, I consider that the present method of calling an incandescent lamp 16 or 20 candle-power is entirely wrong. Incandescent lamps are simply sorted. You put them in at 100 volts or 105 volts, so that they will be even if burned. That is all it means practically. Each consumer of light should fix the candle-power to suit the conditions. The marking that is now done on incandescent lamps is merely nominal; that is, it is in the hands of the parties who use the light to

make the candle-power as much as they like. I wish to express my pleasure at the production of such a paper as this, because, it is of the class that we want. We want more of them in these meetings. It brings to us the results of laboratory work, such as is now being carried on at Cornell, and when we can get such papers, we can count ourselves very fortunate.

DR. OTTO A. MOSES:—I, too, have listened with a great deal of pleasure to the paper and to Mr. Upton's comments upon it, and it carries me back to the day when the determination of candle-power was the all absorbing problem—the day when it was the question whether the incandescent light had any reason for existing or not. However, the concluding remarks of Prof. Nichols open up, I think, the proper field for us to cultivate to-night, and that is the method by which we can arrive at some photometric standard. The method that he proposes has one very great difficulty. He suggests the direction, but it is like pointing to the stars—you may go on to infinity. Carbon, which is the material now used for furnishing the incandescent filament, depends for its atomic condition upon the degree of temperature to which it has been subjected, that is to say, it varies in density and composition. This method struck me as we were listening intently to Prof. Nichols' remarks—if it were possible to surround the light-giving center with some spherical film of definite thickness and containing a certain quantity of a substance to be acted upon by the light, it would be possible by superposing those films, to get, I imagine, what would be the summation of the chemical actions on all the different colors in the spectrum from the dark rays up to those of highest incandescence. In that way, by dissolving out from this film the soluble portions and determining the insoluble matter, it would be possible, by a chemical method, to arrive at the total chemical action on all those films, and in that way make some definite approach to what is the real energy expended by the light. But it is a subject on which I think we can all say with Goethe in his dying moments, "We need light—more light."

PROF. NICHOLS:—If you are not all quite tired of me, I think I could perhaps make the last point a little clearer. The slide did not quite do its duty, I think, in bringing out the relationship between the various wave-lengths of radiation of four lamps all of which give the same candle-power, and from that I think I can indicate to you the line along which I would suggest a change of

standard. I will draw a diagram which, perhaps, will be a little clearer. Suppose this (see Fig. 14) is the spectrum which is assumed to be of unit intensity throughout. This is the yellow (indicating); here is the red; out here is green, blue and then violet, which is the limit of the spectrum. Now, if you have a lamp of the same type of carbon, which corresponds to a 16 can-

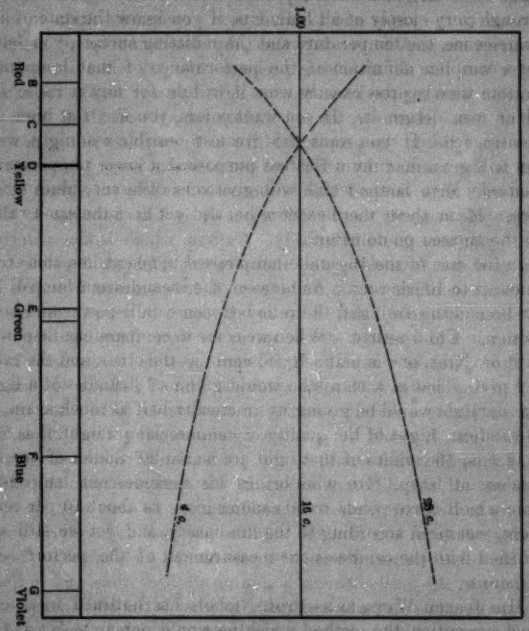

FIG. 14.

dle-power lamp of to-day; take this same lamp and run it at a temperature which corresponds to 4 candle-power to-day, and make that lamp large enough so that the photometer says it gives 16 candles, we find a curve like that which I had in my diagram, of this variety. Here are two lamps, one 16 and the other 4 c. p., and the photometer says that they are the same, but they are not the same either in total amount of energy, as one of my tables

showed you, or in luminous effect; and if we run that on to 28 candles, we find the red very much weaker and the blue correspondingly much stronger. And there are three lamps, all of which the photometer says, give 16 candles, and yet they vary in total luminous energy and in total light-giving value as measured by their luminosity. At any rate, for a single type of carbon, prepared according to a certain process, and I believe it will hold through very closely of all filaments, if you know the state of incandescence, the temperature and the radiating surface, you have got a complete definition of the performance of that lamp, and you can then express exactly what it will do for any purpose for which you design it. If you want colors, you use it at high incandescence. If you want the greatest possible reading power, you will get a maximum for that purpose at a lower temperature. You may have lamps which will give very different values when measured in these more exact ways, and yet give the same value by the Bunsen photometer.

In the case of the 16-candle lamp raised to 50 candles, this error amounts to 10 per cent. As between the incandescent lamp of 16 candle and the arc light, the ratio between candle-power and luminosity is 4 to 5 nearly. When we come to compare candle-power with daylight, one is half as good again as the other, and the ratio is 4 to 6. That is, a man who would give us 16 candles of a light like daylight would be giving us practically half as much again, or 24 candles. Light of the quality of commercial arc light, is as 5 to 4, that is, 16 candles of that light are worth 20 candles of the incandescent lamp. He who brings his incandescent lamp to a state which corresponds to 50 candles gives us about 10 per cent. more, measured according to the luminosity, and yet we still are satisfied with the candle as our measurement of the performance of lamps.

Mr. Joseph Wetzler:—Prof. Nichols has outlined in a very good suggestion, the method which he would pursue to get at the correct method of measuring the candle-power of the lamp, and his method would consist in obtaining the radiating surface of the filament and its temperature. I would like to ask if he has attempted any practical way of carrying that out. Naturally it would seem that the determination of the radiating area of a filament would be easy to accomplish, knowing its size and shape, and then would come the question of the temperature of the filament. It strikes me that if we knew for any particular carbon,

the rate of variation of resistance for increase in temperature, that the latter might be comparatively easily determined, I would like to know if Prof. Nichols has worked in that direction. We would have merely to measure the resistance of the carbon by a method similar to that of the Siemens pyrometer to obtain its temperature, and then, having the temperature and the area we could get at the value which he suggests.

PROF. NICHOLS:—I would say, in reply to Mr. Wetzler's suggestion, that I have been very much discouraged from attempting that, on account of some very singular results which Prof. Anthony obtained some years ago, and which I think he reported to the Institute at that time,[1] in the matter of the behavior of incandescent lamp carbons as to resistance at high temperatures. Supposing that we have a curve along which the resistance is falling off; we should expect it to go on falling off according to a well defined law; but he came across a number of lamps in which this curve turned upward, and at a certain point you would have a very high temperature and a low temperature at which the resistance would be the same. Phenomena of that kind rather deterred me from that method of getting at the temperature of the carbon. But I think there is a hope of getting an optical method, an instrument by which you can look directly at the light and ascertain its temperature in degrees centigrade. I think it would be premature to speak of that now, possibly at some future meeting I may be able to report progress on it.

DR. MOSES:—This is an interesting subject and there are those here who can give us some information which will lead us towards the proper solution of it. Mr. Upton, I am sure, will be able to answer some of these questions for us. In the manufacture of carbons, for instance, from bamboo, in which he perhaps has had more experience than any other living man, the carbons are manufactured of certain dimensions. They are then submitted to approximately a definite temperature, but it is found that they vary considerably in their resistances. Nevertheless, being of the same dimensions, and the carbons, when rendered incandescent, being brought up to a certain definite temperature, irrespective of the resistances in the beginning, it would seem when definite amounts of current were passing, that in spite of this variation in resistance you would finally get the same amount of light, having these dimensions and the same material to act

1. Transactions American Institute of Electrical Engineers, Vol. IV. p. 198.

upon and the same temperature ultimately; the temperature in this case being brought about by the current. Now, if Mr. Upton would tell us about what would be the variations in carbons when of the same dimensions, when any given lot of them are put into lamps, if there would be a variation of as much as 20 ohms.

MR. UPTON:—The ohms vary, of course, from accident. The one constant is the candles per horse-power.

DR. MOSES:—But a definite fact is the amount of current that you allow to pass through them in testing them for their illuminating power. If you were to allow a definite number of watts to pass through those lamps, would you not approximately get the same amount of illumination irrespective of the initial variation in resistance? It is a problem which it seems to me would interest you. You may have tried it and solved it already.

MR. UPTON:—You are stating in a few words a pretty large problem; that is the trouble. Of course, the question of the quality of the carbon comes in, in a very large degree. That has been shown again and again. The one constant, as I said, is the candles per horse-power. The carbons will vary, of course. Referring to what Prof. Nichols says about the falsity of photometric measurements, many of us know that where lamps run a little bright a greater effect would be obtained for certain purposes far in excess of the increase of candle power. That has been noticed in store lighting where colors come in, and Prof. Nichols has explained it. There is another point about lighting that was not mentioned and that is the physical effect, we used to notice that. The moment you get lighting up to a certain brightness, it has a cheering effect. If you have it dull, it has the opposite effect, though both may be giving the same bulk of candle power. I hope I have answered your question.

DR. MOSES:—You have answered it, I think, quite correctly, when you say that we can ultimately get the same quality of carbons, if we carry the temperature of the carbon and keep it there for a time very much higher than the temperature at which the filament was originally carbonized. That is to say, when you take definite dimensions and bring them up, say to a power of 48 candles, and keep them there for some time, you then, so to say, cook that carbon and get just the very condition at which you can make these tests. Now, then, by passing a definite amount of current and bringing the temperature as closely as we can cal-

culate up to 48 candles, would you not then get the same amount of candle power from all of these? That question answered would decide whether it was possible to use this filament as a photometric standard. That was the point we were originally discussing.

MR. UPTON:—As I said in reference to using a filament for photometric standard, carbon varies in the character of its surface, and you must specify your carbon and specify its carbonization before you can take it as a standard. You take a black carbon or gray carbon, or polished carbon and all the grades running between those, and you will have a variation in candle power. The dimensions do not fix the candle power. It is the quality of the surface that fixes the candle power to a large degree.

DR. MOSES:—But may we not get that quality of surface by bringing it to the same high intensity, by using a definite amount of current, and then determining whether those carbons do not furnish at the same amount of horse power consumed, the same amount of light.

MR. UPTON:—No. Take a thin flash carbon; you bring that up high and it has changed its quality; and the power it will take to give a certain light will change. Incandescent lamps depend on the surface, temperature does not fix it, as far as I know. Of course the temperature changes with the cooling effects; and to measure the temperature of the filament itself is a very difficult matter. I do not know how to do it at present.

DR. MOSES:—The meeting must pardon my keeping up the conversation, but I am reminded of Dr. Draper's experiments—the classical ones—where it was necessary to bring the object up to about 1,000 degrees of temperature before it became luminous. Now, we have got our conversation up to that point, and I hope we shall continue it in order to get results from it. Nature indicates a very definite chemical composition in her vegetable products. It is true any fibre will vary in different parts of the plant, and there will be a difficulty again; but since Mr. Upton, I believe, is careful to have them all from the same radial distance from the axis of the plant, on that account we may consider that the material is homogeneous and uniform. But when we raise a body to a given temperature we drive off those substances that may be distilled off, and if we finally get a definite amount of temperature, entirely irrespective of its composition in the beginning, and then put a definite amount of current

through a definite parallelopipedon of carbon, we ought to get a definite amount of illumination. Now, then, would not the same cross-section and hence the same areas of similar carbons give exactly the same amount of light? My reason for pressing the question is to determine whether the suggestion of Prof. Nichols may not ultimately be taken as the definite photometric standard. Now the platinum method has obvious disadvantages, from experiments which have become classical, made at the laboratory at which Mr. Upton assisted, where platinum was discovered to be constantly changing its condition in a vacuum and constantly giving off its surface under the bombardment of the particles combined with some action of the current, and it is not by any means constant. So that carbon may be a better material than platinum. Nevertheless they, and all other substances are varying constantly. So that it is scarcely to be hoped that it will be ever taken as a standard. It is, however, so easy to obtain these standards, and they can be so easily renewed, that perhaps they may be ultimately adopted as such.

MR. MAILLOUX:—The constitution of carbon, as it occurs in the incandescent lamp, is to a large extent an artificial one, and one which is dependent greatly upon the method of treatment. You may say, for instance, that the value of a carbon filament would depend, other things being equal, on the density of the carbon. No doubt that density has some relation to the color of it and that again the color has some relation to the condition of the surface, whether it is granular, and whether it is crystalline, and whether it is smooth and polished. Now, it occurs to me that it may be that this variation of resistance in the incandescent lamp filament is one, which instead of being abnormal, is perfectly normal and characteristic of carbon in a highly incandescent state. May it not be that the resistance of carbon varies with its density and that this attains a minimum at a certain point. I am brought to this idea by a certain analogy with substances which are perfectly familiar to us—electrolytes. I have had considerable experience in electrolysis, and have had to determine the specific resistance of a great many substances, and I find that a great many—I will not say all—but a large number of chemical substances used in electrolysis have the very peculiar property, that there is a particular density at which they give the minimum resistance. For instance, with sulphuric acid, which is so extensively used now-a-days in storage batteries, the curve is a very peculiar one; a

very small increase at first in specific gravity, where you start with pure water, will make a very large decrease of resistance, but at a specific gravity of 1.2 you have reached very nearly the minimum, and beyond that the resistance increases, and finally, when the sulphuric acid is at its maximum density, the resistance will become quite high and the curve presents a very striking analogy indeed to that which Prof. Anthony presented before the Institute in his paper referred to by Prof. Nichols. Moreover, it is found that each class of salt—take the sulphates for instance—gives a series of lines which have the same general character of curvature, and no doubt they are amenable to one general form of equation, and may it not be that we have here to deal with a phenomenon which is entirely normal, and that when we once determine the particular law which would appear to be involved here, we would have right there a means of measuring the efficiency of the lamp. Having found an expression for the law which connects the density of the carbon with the temperature or with the resistance in some way, we shall have made some step toward the finding of a practiced method of gauging the efficiency of incandescent lamps. As I understand it, Prof. Nichols states that the ideal method would be one which would be based on the radiation of the energy from the filament of the incandescent lamp itself, and if that were the case, it looks to me as though you must look right there for the path leading to the proper solution.

Dr. Wheeler:—It seems to me that the most important measurements to be made are of actually existing lights—not ideal ones; and for that reason I would like to know if Prof. Nichols thinks that the sums of the photometer readings of a light in different parts of the spectrum represent its real value.

Prof. Nichols:—Mr. President, as I understand it, we have to multiply the photometer reading in each part of the spectrum by a factor which itself is a function of the wave-length and which expresses the light-producing power of that particular wave-length. I can, perhaps, illustrate this by means of a curve. Suppose you have a light of this kind. (Illustrating.) That is the distribution of energy in the spectrum from the violet to the red, and you take the sum of those wave-lengths right down. The integrated value of this energy, that is the area enclosed by this curve, is the quantity which I speak of as the total luminous energy or radiation; but that is not the light-giving power.

The light-giving power varies enormously in different parts. Now, the product of the ordinates of the two will give you the total light-giving power of the spectrum. Out of the red we get great energy and little light-giving power and at the end of the spectrum our luminosity ceases. We have to take, in the case of each wave-length, the product of the amount of energy and its luminosity as determined by one of the methods described; that is the power which that particular wave length has in enabling us to read fine print. If you take the blue light and yellow light in the spectrum, and bring them to the same brightness so that to the best of our average judgment we would say that they were equally bright; then take fine print and put it in the yellow, you can read it there, but put it over in the blue and you cannot read it. In other words, the power of the blue to enable us to distinguish print is less. It is of no value, practically, for that purpose. The rays which enable us to distinguish black characters on a white ground are located in that half of the spectrum which lies toward the red, and the rest might as well be thrown away. In almost all uses of the electric light the feature which Mr. Upton spoke about comes in, namely, that indescribable value, that quality which brings out the colors in the art galleries and in our rooms. That lies largely in the violet, so that I think the *value* of light increases with its incandescence faster than its luminosity does. It is a factor which must be determined for each case according to the purposes for which you intend to use the light.

DR. MOSES:—It is a sad thing for one to admit that we have to determine all these questions ultimately by an imperfect instrument. The eye has to be the final umpire of these measurements, and we can scarcely consider the action of the eye as an accurate means of determining this question. If the eye is used under certain circumstances in direct light we find that it undergoes a kind of paralysis; there is a neutralization of light upon the retina, so that our own powers of observation are affected by these varying conditions, and I do not see how it is ever to be possible for us, except by using special determinations for special purposes, to arrive at a result. I have many a time seen the cobblers in Germany sewing, their stitches being exactly in the focus of a globe of water, with the smallest kind of a farthing dip at the other side, giving a concentration of light at the very point at which it was needed. They got a better light for their purpose than had they been working in the full glare of an arc light. We

have to consider the conditions, and it is there we have ultimately to determine according to the necessity of the case.

MR. DOBBIE:—I would like to ask Prof. Nichols if he has thought of a photographic method of determining this. There are three points in the spectrum which could each be determined by a plate specially prepared for it. For instance, a dry plate can be dyed by aniline and made sensitive to one particular ray. As the question of lighting is a commercial question, might it not be a practical thing to determine the power of the lamp in a special part of the spectrum by a plate and give it that value and state in what part of the spectrum its value was given for. I believe that the yellow is most commonly used, but for photography there would of course be a call for the shorter wave lengths of the blue rays.

MR. BIRDSALL:—I have given some thought at different times to photographic methods of measuring light. The fact that I have also dabbled in photography has been rather discouraging. As it is quite well known that ordinary silver salts are more sensitive to the blue and violet rays than to others, and almost unaffected by the dark red rays, that would seem to give us a means of measuring the most desirable rays for colors, namely, the violet rays; but it is also a fact that right good photographs have been taken in almost absolute darkness to ordinary eyes. In other words, the violet rays past the visible end of the spectum have the power to affect the sensitive plate, and in that way in Germany photographs have been taken at night; that is, at night when there was no starlight of any kind, it being fairly cloudy, in which the conditions were those of almost absolute darkness. Speaking about the varying density of carbon and the great variety of effects you can get from apparently uniform treatment and conditions, all photographers know that gelatine has the same elegant property; with the same treatment you can get quite varying results within 100 per cent.

MR. MAILLOUX:—I would differ with Dr. Moses as to the eye being made the ultimate arbiter of the efficiency of the incandescent lamp, and I believe that it will be found possible to measure the energy of the incandescent light by other means. I have great faith in the calorimeter, and I believe strongly in the method which was outlined this evening by Prof. Nichols. I do not see that there are any physical impossibilities lying in the way of our arriving at such a method by which we can differentiate the various kinds of light, and get the sum of the different kinds and find

out the law connecting them together. Having done this, then it occurs to me that we could express the efficiency with reference to the properties for which the light is to be used and that we could have a sort of *modulus*, as it were, by means of which the varying conditions of the use of the lamps would be taken into consideration in estimating their particular efficiency.

A MEMBER:—It strikes me that what we want to get at is a practical method of determining the value of a lamp for every day use. We can't use fine methods. It amounts mathematically to trying to fix a curve with one point while we want to know three points of that curve at least. If we have some practical method of determining the three points of that curve instead of one, the matter would be solved for all practical purposes. Suppose we select the line in the spectrum. That is, practically, what is selected now. When we use the candle the other two ends of the spectrum are allowed to go up or down just as they please. Perhaps by some method the two ends of the illuminating power might be fixed. For instance, in determining the illuminating power, instead of selecting a white glass, select two others and give the candle-power through three instead of one.

DR. WHEELER:—I do not think that I made my question quite clear. I would like to try it again. In measuring the power of the light I understand, of course, there are three sets of rays, one of heat and one of light and one actinic, and to know how much illumination the source gives, we do not care anything about the first or the third, what we want to measure is the second set. Now you get the value of say the yellow part. Then, if you run the incandescence of that lamp up, may you not get a less proportion of yellow and a larger proportion in some other parts of the spectrum, so that while the yellow would read lower, yet the total amount of illumination would perhaps be the same?

PROF. NICHOLS:—I think one of the slides which I showed answers the question—that one deduced from the experiments of Schumann, in which it is found that as the incandescence increases this curve simply rises—one curve over another in this way (illustrating), but not strictly so that the line passing through the tops is a vertical line. There is a continual tendency for the line to work off this way, and if you were to carry it on to a degree of incandescence equal to that of the sun, you would then find the effect just described, that is to say, these curves would lie side by side; but, of course, the range of intensity with which we deal with artificial lights is very much less than between the sun and

any artificial lights. Now, the difference of wave length between these maxima has been determined; in the sun it is 582, and in this case (indicating) it is only shifted to 592, so that for the rays of incandescence which we have to deal with in artificial light, you may say that the whole thing rises together.

THE CHAIRMAN:—It is long past our usual hour for adjournment, but I think we have very far from exhausted the subject. It is in fact impossible to begin to exhaust such a subject in an evening's discussion, even so full and able a discussion as we have had. I think we appreciate our own ignorance in dealing with such a question. It is remarkable how far in advance our own speculations and ideas of the subject are, of the ideas which are ordinarily entertained by the public, and while listening to the discussion this evening as to candle-power, I was reminded of an incident that occurred last week in Bristol, Pennsylvania, where one of the large drug stores of the town was illuminated by candles at the time of the starting of the incandescent lamps. The druggist had heard that the incandescent lamps were of 16 candles, and in order to show how poor and insignificant the new illuminant was, he decorated the whole of his window with 16 candles. The result of the illumination was not as great a success as he anticipated, and he was overwhelmed with offers of the loan of snuffers on all sides. Although the incandescent lamp compared so favorably with the candles that were shown by the Bristol druggist, I think we have before us a great deal to do with the improving and perfection of our arc and incandescent lamps in order to secure a greater efficiency and in order to be less wasteful. The lines of one of England's great poets occur to me in that connection. You may remember them; they are those in which Tennyson says:

> "Our little systems have their day,
> They have their day and cease to be,
> They are but broken lights of Thee,
> And Thou, O Lord, art more than they."

And when we can get our own broken lights somewhat nearer the perfection of daylight we shall have done some of the work which awaits us. Of course, Tennyson, in speaking of "Our little systems" having their day, did not have in mind the systems which we see in such rapid process of consolidation with other larger systems. (Laughter.) At the same time I think he hinted at a very great and singular truth.

Adjourned.

— INDEX —

OF

CURRENT ELECTRICAL LITERATURE,

&c. (January, 1889.)

TELEGRAPHY, SIGNALING, ETC.

Electric Water Level Indicator and Recorder. (Ill.) *Sci. Am. Supp.*, Jan. 26, p. 10,894.

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The Telephone in Austria. R. H. Krausse. *N. Y. Elec. Rev.*, Jan. 26, p. 7.

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The Richardson Arc Lamp. (Ill.) *Elec. World*, Jan. 12, p. 20.

The Bargin Arc Lamp. (Ill.) (M. Hippolyte Fontaine, "Eclairage à l'Électricité.") *Lond. Elecn.*, Jan. 11, p. 282.

High and Low Tension Arc Light Systems. F. B. Badt. *West. Elecn.*, Jan. 26, p. 43.

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The Westinghouse Electric System. (Ill.) *Eng.*, Jan. 8, p. 56.

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New Stations of the Edison Company. *N. Y. Elec. Rev.*, Jan. 12, p. 9.

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Train Lighting by Electricity. *West. Elecn.*, Jan. 12, p. 21.

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Chicago City Electric Light Plant. (Ill.) *West. Elecn.*, Jan. 5, p. 1; Jan. 12, p. 15.

Electric Lighting in San Diego, Cal. *N. Y. Elec. Rev.*, Jan. 19, p. 8.

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Great Electric Lighting Works. *N. Y. Elec. Rev.*, Jan. 5, p. 10. (Berlin, Paris, Vienna, Brussels.)

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The Electric Light in Land Warfare. *Lond. Elecn.; Science*, Jan. 11, p. 22.

Electric Lighting Schemes in the Metropolis. (Ed.) *Eng.*, Jan. 4, p. 13.

Auxiliary Engines at the Deptford Electric Light Station. (Ill.) *Indust.*, Jan. 4, p. 12; *Eng.*, Jan. 11, p. 30.

A Remarkable Incandescent Lamp. (English.) *Times; Elec. World*, Jan. 12, p. 19.

Incandescent Lamps and Storage Batteries. (Corr.) C. W. F. *Elec. World*, Jan. 12, p. 16.

Guard Against Incandescent Lamp Breakage. (Ill.) *West. Elecn.*, Jan. 5, p. 4.

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Flashed Filaments in Lamps. (Corr.) S. P. Thompson. *Lond. Elecn.*, Jan. 4, p. 261.

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Insulation Resistance of Electric Lighting Installations. (Ill.) A. Jamieson. (Instn. of Elec. Engrs.) *Indust.*, Jan. 25, p. 89; *Lond. Elec. Engr.*, Jan. 25, p. 80; *Lond. Elecn.*, Jan. 25, p. 340.

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"Electricity, Light and Heat." C. F. Brackett. N. Y. Elec. Club. *Md. Lt & Ht.*, Jan. 10, p. 34; *N. Y. Elec. Rev.*, Jan. 12, pp. 1–6.

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Professor Brackett's Address before the Electric Club. *Elec. World*, Jan. 12, p. 22.

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The Alternating Dynamo of the Thomson-Houston Electric Company. (Ill.) *Elec. World*, Jan. 12, p. 19.

The Denison Motor and Dynamo. (Ill.) *Elec. World*, Jan. 19, p. 28.

The Continental Dynamo. (Ill.) *Elec. World*, Jan. 5, p. 2; *Science*, Jan 11, p. 17.

The Hall Dynamo. (Ill.) *Indust.*, Jan. 4, p. 21; *West. Elecn.*, Jan. 26, p. 41.

The Helvetia Dynamo. (Ill.) *West. Elecn.*, Jan. 12, p. 18.

The "Silvertown" Dynamos. (Ill.) *N. Y. Elec Rev.*, Jan. 5, p. 8.

New Wheel-Armature Dynamo Machine. (Ill.) *Lond. Elec. Rev.*, Jan. 18, p. 61.

A 10,000-Volt Transformer for Testing Insulation Resistance. (Ill.) *Lond. Elecn.* Jan. 11, p. 281; *N. Y. Elec. Engr.*, Jan., p. 23; *Sci. Am. Supp.*, Jan. 12, p. 10,865.

On the Relative Proportions of Ring Armatures. (Ill.) *Elec. World*, Jan. 26, p. 43.

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Elastic Foundations for Dynamos. (Note.) *Lond. Elec. Engr.* Jan. 18, p. 43. (M. G. Anthoni.)

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The Danger of Electric Distribution. *Sci. Am.*, Jan. 12, p. 16.

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Notes on Electro-Magnetic Induction. (Ill.) J. A. Fleming. (Cont'd from p. 216.) *Lond. Elecn.*, Jan. 4, p. 244; Jan. 11, p. 272; Jan. 18, p. 300.

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The Electric Motor in Novel Mining Operations. *Elec. World*, Jan. 12, p. 17. (Pumping out the Big Bend River shoals.) *Lond. Elec. Engr.*, Jan. 25, p. 67.

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Electrical Coal Cutting Machines. (Bower & Co.) *Lond. Elecn.*, Jan. 11, p. 282.

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Application of Motors to Traveling Cranes. *Elec. World*, Jan. 19, p. 28.

Electric Tree Felling Machine. (Ill.) *Indust.*, Jan. 11, p. 43.

The Electric Transmission of Power. W. E. Ayrton. (Drill Hall, Bath.) *Elec. Pr.*, Jan., p. 10.

Mechanical Regulation of Electric Motors. R. B. Owens. (Ill.) *Elec. World*, Jan. 26, p. 42.

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The Electric Motor Field. A Month's Record. *Elec. Pr.*, Jan., p. 21.

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Electric Power Distribution in New York City. *Elec. Pr* , Jan., p. 14.

The Kearney, Neb., Water Power and Electric Distribution Plant. D. C. Jackson. *Elec. Pr.*, Jan., p. 17.

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The Alternating Current Motor. (Westinghouse.) *Elec. Pr.*, Jan., p. 16.

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Electric Motors for Steam Railways. *Ry. Rev.*; *Elec. Pr.*, Jan., p. 3.

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The Danville Electric Railway. (Ill.) *N. Y. Elec. Rev.*, Jan. 5, p. 3.

The Thomson-Houston Electric Road, Nashville, Tenn *Elec. World*, Jan. 19, p. 36; *N. Y. Elec. Rev.*, Jan. 19, p. 8.

The Electric Railway at Washington, D. C. (Ill.) *Elec. World*, Jan. 26, p. 46.

The Omaha and Council Bluffs Electric Railway. (Ill.) *Elec. World*, Jan. 26, p. 45; *N. Y. Elec. Rev.*, Jan. 26, p. 8; *Md. Lt. & Ht.*, Jan. 31, p. 121.

Some New Thomson-Houston Electric Roads. *Elec. World*, Jan. 26, p. 48. (Des Moines, Ia, Syracuse, N. Y., Wichita, Kan., Scranton, Pa.)

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A Blizzard on an Electric Road in the West. *Elec. World*, Jan. 19, p. 36; *Science*, Jan. 25, pp. 56–60.

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Another Victory for Electricity. *Md. Lt. & Ht.*, Jan. 3, p. 13. (West End Street Ry., Boston.)

New Sprague Road in Chattanooga, Tenn. *N. Y. Elec. Rev.*, Jan. 5, p. 3; *Science*, Jan. 11, p. 23.

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The Sprague Electric Railway at Cleveland, O. *Elec. World*, Jan. 12, p. 22; Jan. 26, p. 48; *West. Elecn.*, Jan. 12, p. 21.

New Design Elevated Electric Railroad. (Ill.) *N. Y. Elec. Rev.*, Jan. 12, p. 1.

The White Elevated Electric Railroad. (Ill.) *Science*, Jan. 18, p. 33.

Electric Cars on Elevated Railroads. *Md. Lt. & Ht.*; *Elec. Pr.*, Jan., p. 19.

Experiments with the Daft Electric Railway Motor "Benjamin Franklin." *Elec. World; Lond. Elec. Rev.*, Jan. 4, p. 12.

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The Conduit System of Electric Railways. G. R. Blodgett. *Elec. Pr.*, Jan., p. 7.

The New Bentley-Knight Standard Motor Truck and Conduit. (Ill.) *Elec. World*, Jan. 12, p. 18.

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Some Considerations Concerning the Electric Locomotive. David E. Lain. *Elec. Pr.*, Jan., p. 4.

Electric Traction. (Corr.) T. Parker. *Lond. Elecn.*, Jan. 4, p. 262. A. Reckenzaun. Jan. 11, p. 286.

Coupling a Dynamo to a Car-Axle. *Sci. Am.*, Jan. 19, p. 32.

Electric Haulage in the Anthracite Mines. A. W. Sheafer. *Elec. Pr.*, Jan., p. 18. (Lykens' Valley Coal Co.)

Radcliffe Ward's Electric Omnibus. (Ill.) *Lond. Elec. Engr.*, Jan. 25, p. 69; *Lond. Elec. Rev.*, Jan. 25, p. 93.

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PRIMARY BATTERIES.

Capacity of the Simple Plunge Battery. (Corr.) C. D. Parkhurst. *Sci. Am.*, Jan. 19, p. 37.

An Inexpensive Cell for Galvanism. A. H. Buckmaster. *Sci. Am. Supp.*, Jan. 26, p. 10,894.

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Primary Batteries for Large Currents. (Ill.) (Corr.) N. G. Thompson. *Lond. Elecn.*, Jan. 11, p. 286.

Caustic Potash and Bromine Elements. (Note,) Herr Koosen, *Wiedemann's Annalen; Lond. Elecn.*, Jan. 11, p. 270.

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New Secondary Batteries. *Science*, Jan. 18, p. 35. (The "Macraeon" and the "Detroit.")

Lugo's Novel Storage Battery. *Elec. World*, Jan. 26, p. 44.

The New Gibson Storage Battery. (Ill.) *Elec. World*, Jan. 19, p. 28.

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The Storage of Electricity. (Ill.) *Science*, Jan. 25, p. 53.

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The Transition from Metallic to Electrolytic Conduction. C. Barns. *Am. Jour. Science; Elec. World*, Jan. 12, p. 17.

Electrolytic Method of Liquefying Gases. (Note.) H. N. Warren. *Jour. Chem. Soc.; Lond Elec. Engr.*, Jan. 25, p. 67.

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The Electrolysis of Common Salt. *Elec. World*, Jan. 5, p. 5.

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The Hermite Electro-Chemical Bleaching Process. (Ill.) *Lond. Elecn.*, Jan. 18, p. 306; *Lond. Elec. Rev.*, Jan. 18, p. 58; *Lond. Elec. Engr.*, Jan. 18, p. 56; *Indust.*, Jan. 18, p. 65.

ATMOSPHERIC ELECTRICITY.

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Globular Lightning. (Note.) *Lond. Elecn.*, Jan. 11, p. 271.

UNDERGROUND WIRES, ETC.

Gas Mains as Electrical Conduits. (Ill.) *Elec. World*; *Lond. Elec. Rev.*, Jan. 11, p. 46; *Lond. Elec. Engr.*, Jan. 25, p. 67.

Statistics of Wires in Brooklyn. *Elec. World*, Jan. 5, p. 3.

The Buried Wires of Brooklyn. Annual Report of the Subway Commissioners. *N. Y. Elec. Rev.*, Jan. 5, p. 6.

Conduits for Electric Light Lines. *N. Y. Elec. Rev.*, Jan. 19, p. 13. (Wash. & Va. Conduit Co.)

Underground Mains. (Corr.) *Lond. Elec. Rev.*, Jan. 11, p. 52.

Second Report of the Board of Electrical Control for the City of New York. *Lond. Elec. Rev.*, Jan. 25, p. 86.

Annual Report of the New York Board of Electrical Control. (Ill.) *Elec. World*, Jan. 12, p. 21. Meeting of Board of Electrical Control, Jan. 26, p. 48.

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The Subway Fight of the United States Company. *Elec. World*, Jan. 12, p. 22.

INSTRUMENTS, MEASUREMENTS, ETC.

Six Years' Practical Experience with the Edison Chemical Meter. (Ill.) W. J. Jenks. Am. Inst. Elec. Engrs. *Elec. World*, Jan. 5, p. 6; *Lond. Elec. Rev.*, Jan. 11, p. 45; Jan. 25, p. 90; *N. Y. Elec. Engr.*, Jan., pp. 7–31; *West. Elecn.*, Jan. 5, p. 7.

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The Electrical Testing Bureau of the Johns Hopkins University. *N. Y. Elec. Rev.*, Jan. 5, p. 9.

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Electric Thermometer. (Note.) M. Chaperon. *Lond. Elec. Engr.*, Jan. 4, p. 3.

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A New Form of Condenser. (Ill. Corr.) W. Perren-Maycock. *Lond. Elec. Rev.*, Jan. 4, p. 24.

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An Electric Magic Lantern. (Ill.) *Elec. World*, Jan. 12, p. 16.

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The Cowles Process. (Note.) *Lond. Elec. Engr.*, Jan. 11, p. 25.

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Improvements in Electric Fixtures. (Ill.) *N. Y. Elec. Rev.*, Jan. 19, p. 1. (Mitchell, Vance & Co.)

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A New Method of Tracing Curves by Photography. Eric Gérard. Academie des Sciences de Belgique. *Elec. World*, Jan. 12, p. 19; *Lond. Elecn.*, Jan. 18, p. 299.

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Heating by Electricity. *Md. Lt. & Ht.*, Jan. 10, p. 33.

An Electrical Type Writer. W. W. Ker. *Md. Lt. & Ht.*, Jan. 10, p. 41.

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Chicago Electric Club. *West. Elecn.*, Jan. 19, p. 35; Jan. 26, p. 49.

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MECHANICAL.

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The Baker Common Sense Oil Filter. (Ill.) *Elec. World*, Jan. 5, p. 5.

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NAME.	ABBREVIATION.	PUBLISHED, &c.
Engineer.	*Engr.*	London, 163 Strand, weekly. £1.9.
Engineering.	*Eng.*	London, 35–36 Bedford St. W. C.; weekly. £1.16.
Industries	*Indust.*	Manchester, 70 Market St., weekly. £1.12.
The Electrician.	*Lond. Elecn.*	London, 1 Salisbury Court, E. C.; weekly. £1.2.
The Telegraphic Journal and Electrical Review.	*Lond Elec. Rev.*	London, 22 Paternoster Row, E. C.; weekly. £1.1.8.
The Electrical Engineer	*Lond. Elec. Engr.*	London, 139–140 Salisbury Court; weekly, 17s. 4d.
Nature.	*Nat.*	London, 29 Bedford St., W. C.; weekly, £1.8.
The Electrical Engineer	*N. Y. Elec. Engr.*	New York, 11 Wall Street; monthly, $3
The Electrical World.	*Elec. World.*	New York, 168–177 Potter Building; weekly. $3
The Electrical Review.	*N. Y. Elec. Rev.*	New York, 13 Park Row; weekly. $3.
The Electric Age.	*Elec. Age.*	New York, 5 Dey Street; semi-monthly, $1.50.
Modern Light and Heat.	*Md Lt and Ht.*	Boston, 146 Franklin Street; weekly, $3.
Western Electrician.	*West. Elecn.*	Chicago, 6 Lakeside Building; weekly, $3.
Electric Power.	*Elec. P'wr.*	New York, 150 Broadway; monthly, $3.
The Electro-Mechanic.	*Elec. Mech.*	Kansas City, Mo; semi-monthly, $2.
Practical Electricity.	*Prac. Elec.*	Boston, 620 Atlantic Ave.; monthly, $1.
Journal of the Franklin Institute.	*Jour. Fkln. Inst.*	Philadelphia, Franklin Institute; monthly, $5.
Science.	*Science.*	New York, 47 Lafayette Place, weekly, $3.50.
Scientific American.	*Sci. Am.*	New York, 361 Broadway; weekly, $3.
Scientific American Supplement.	*Sci. Am. Supp.*	New York, 361 Broadway; weekly, $5.
Mechanics.	*Mech.*	Philadelphia, 907 Arch St.; monthly, $1.
Railroad Gazette.	*R'd. Gaz.*	New York, 73 Broadway; weekly, $4 20.
Street Railway Journal	*St. Ry. Jour.*	New York, 113 Liberty St.; monthly, $2
Street Railway Gazette.	*St. Ry. Gaz.*	Chicago, 9 Lakeside Building; monthly, $2.
Light, Heat and Power.	*Lt. Ht. and Pr.*	Philadelphia, Drexel Building; weekly, $4.
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Vol. I, 1884.

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Vol. II, 1885.

THE PROTECTION OF ELECTRICAL INVENTIONS. F. Jannus, of Washington, D. C.—COST OF MINE LIGHTING. Frank P. Mills, now of Ishpeming, Mich.—THE ELECTRIC ARC LAMP FRICTIONAL CLUTCH. (Illustrated.) By Edward P. Thompson of New York.—DESCRIPTION OF A LARGE SECONDARY BATTERY PLANT FOR GENERAL COMMERCIAL DISTRIBUTION. E. P. Roberts, of Cheyenne, Wyo.—DELANY'S SYSTEM OF FAC-SIMILE TELEGRAPHY. (Illustrated.) Prof. Edwin J. Houston of Philadelphia.

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UNDERGROUND ELECTRICAL SYSTEMS. By Sidney F. Shelbourne.—THE GREAT TANGENT GALVANOMETER OF THE CORNELL UNIVERSITY. Prof. W. A. Anthony, now of Manchester, Conn.—SOME RECENT ADVANCES IN TELEPHONY. (Illustrated.) Thomas D. Lockwood, of Boston, Mass.—THE PATENT OFFICE AND PATENT OFFICE PRACTICE. A. C. Fowler, of New York.—STATIC DIFFICULTIES IN TELEGRAPH WIRES. F. W. Jones of New York. Containing a Synopsis, with reference to 113 American and Foreign Patents for Inventions intended to overcome these difficulties.—SECONDARY BATTERIES FOR LIGHT AND POWER. A. H. Bauer.—THE WIRE GAUGE. Report of Committee.—NOTES ON DYNAMO INDUCTION. Sidney F. Shelbourne.

Vol. IV, 1887.

ELECTRIC STREET CARS. T. C. Martin, of New York.—THE PRACTICAL REQUIREMENTS OF SMALL MOTORS. S. S. Wheeler, of New York.—DISTRIBUTION OF ELECTRICITY BY SECONDARY GENERATORS. Discussion by F. L. Pope, Dr. Otto A. Mosse, Captain O. E. Michaelis, Prof. Elihu Thomson and others.—STORAGE BATTERIES IN PRACTICE. E. P. Roberts, of Cheyenne, Wyo.—DIFFERING TEMPERATURE COEFFICIENTS OF THE DIFFERENT COILS OF A FINE RHEOSTAT. Prof. W. A. Anthony, now of Manchester, Conn.—ON THE BEST RATIO OF THE SER[illegible]ON OF THE GRAMME ARMATURE TO THE SECTION OF THE FIELD MAGNETS. (Illustrated.) Dugald C. Jackson, now of Lincoln, Neb.—NOTES ON PHENOMENA OF ALTERNATING CURRENTS. (Illustrated.) Prof. Elihu Thomson, of Lynn, Mass.—A FEW COMPARATIVE STATISTICS OF ELECTRIC RAILWAYS. T. C. Martin, of New York. (With tabular statement.)—CENTRAL STATION CONSTRUCTION. J. F. Powers, of Troy, New York.—ON THE CHANGE FROM NEGATIVE TO POSITIVE BY THE TEMPER

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Vol. V, 1887-8.

ON ELECTRIC STREET CARS, WITH SPECIAL REFERENCE TO METHODS OF GEARING. Anthony Reckenzaun, of London. No. 1, October, 1887.—A COULOMB METER, OR INSTRUMENT FOR MEASURING THE CONSUMPTION OF ELECTRICITY. (Illustrated.) Prof. George Forbes, F.R.S., of London. No. 2, November, 1887.—RECENT IMPROVEMENTS IN APPARATUS FOR OCEAN CABLING. (Illustrated.) Charles Cuttriss. Supplementary Note on the Siphon Recorder, and Ocean Telephony, by Thos. D. Lockwood. No 3, December, 1887.—PHENOMENA OF RETARDATION IN THE INDUCTION COIL. (Illustrated.) William Stanley, Jr. No. 4, January, 1888.—REVISION OF THE PATENT LAW. Arthur Steuart, Esq. No. 5, February, 1888.—ELECTRIC ENERGY FROM CARBON WITHOUT HEAT. Willard E. Case, Auburn, N. Y. No. 6, March, 1888.—ALTERNATING CURRENT ELECTRIC MOTORS. Dr. Louis Duncan, Baltimore, Md. No. 7, April, 1888.—MAXIMUM EFFICIENCY OF INCANDESCENT LAMPS. (Illustrated.) John W. Howell. No. 8, May, 1888.—PROTECTION OF THE HUMAN BODY FROM DANGEROUS CURRENTS. Patrick B. Delany.—THE POSSIBILITIES AND LIMITATIONS OF CHEMICAL GENERATORS OF ELECTRICITY. Francis B. Crocker. No. 9, June, 1888.—ON COMPENSATED RESISTANCE STANDARDS. (Illustrated.) Edward L. Nichols. A NEW SYSTEM OF ALTERNATE CURRENT MOTORS AND TRANSFORMERS. (Illustrated.) Nikola Tesla. UNDERGROUND ELECTRICAL CONDUCTORS IN EUROPE AND AMERICA. Prof. G. W. Plympton. THE PATENT COURT AND UNIFORMITY IN PATENT OFFICE PRACTICE. George H. Stockbridge. A SWINGING ARM GALVANOMETER. (Illustrated.) George S. Moier. No. 10, July, 1888. THE SOLUTION OF THE MUNICIPAL RAPID TRANSIT PROBLEM. (Illustrated.) Frank J. Sprague. No. 11, August, 1888. SOME OBJECTIONS TO THE OVERHEAD CONDUCTOR FOR ELECTRIC RAILWAYS, M. B. Leonard. NOTE ON GEARING FOR ELECTRIC RAILWAY MOTORS, Almon Robinson. No. 12, September, 1888.

Vol. VI, 1889.

[Including October, November and December, 1888.]

THE GEYER-BRISTOL METER FOR DIRECT AND ALTERNATING CURRENTS. [Illustrated.] Prof. William E. Geyer. THE ABDANK MAGNETIC CALL AND THE ABDANK INTEGRAPH. [Illustrated.] B. Abdank-Abakanowicz. No. 1, January, 1889. SIX YEARS PRACTICAL EXPERIENCE WITH THE EDISON CHEMICAL METER. (Illustrated.) W. J. Jenks. No. 2, February, 1889. LIGHTNING ARRESTERS AND THE PHOTOGRAPHIC STUDY OF SELF-INDUCTION. (Illustrated.) E. G. Acheson. No. 3, March, 1889. A NEW SYSTEM OF MULTIPLEX TELEGRAPHY. (Illustrated.) Lieut. F. Jarvis Patten. LIGHTNING ARRESTERS AND THE PHOTOGRAPHIC STUDY OF SELF INDUCTION. Notes by Jo. Stanford Brown and Chas. T. Child. REPLY TO THE NOTES OF MESSRS. BROWN AND CHILD by E. G. Acheson. No. 4, April 1889. THE EFFICIENCY OF METHODS OF ARTIFICIAL ILLUMINATION. Illustrated.) Edward L. Nichols. No. 5, May, 1889.

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